

CHIP-SCALE DIFFRACTION PHASE MICROSCOPY

BY

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DISSERTATION

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Abstract

The invention of the bright-field microscope helped scientists image cells as early as the seventeenth century; however, it was not until the 1930's when Fritz Zernike invented the phase contrast microscope that transparent objects could be imaged without labeling. With the invention of photodetectors, quantitative phase imaging (QPI) developed, bringing with it sensitive and quick measurements containing height and refractive index analyses. Additionally, non-invasive imaging of transparent samples became possible. Though numerous QPI methods exist, diffraction phase microscopy (DPM) is notably advantageous. Its benefits include: 1) noise cancellation, 2) the ability to noninvasively image diverse samples, and 3) fast image acquisition.

Due to its success in many applications, including cell imaging and semiconductor metrology, the author proposes scaling down the macro-scale system to implement the Mach-Zehnder-based interferometer on-chip. An on-chip model introduces additional advantages, including 1) space-saving properties, 2) reduction in material consumption and, thus, the cost of the optical system, and 3) reduction in the alignment error of the system. DPM on-chip also has the potential to be used in a new application: portable microscopy. If DPM on-chip is integrated as an add-on module to a cellphone camera, the image processing could be executed within a cellphone application. Such a system might prove useful in biological labs with limited space for testing instruments. It might also be beneficial in biology classrooms that attempt to spark curiosity within younger citizen scientists.

The author will present optimized design parameters, fabrication techniques for key components, and potential applications for the device given its reduced field-of-view. Final results of the optimized system will be discussed followed by an explanation of future work that seeks to improve the outcome.

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1. Quantitative Phase Imaging Motivation

During its proliferation in the seventeenth century, bright-field microscopy made a notable contribution to science: it helped researchers visualize the smallest structures that compose all living matter, thus, establishing the field of cell biology [1]. This new ability to qualitatively inspect opaque objects with magnified views helped scientists discover bacteria, protozoa, and many other organisms in the late 1600's. Today, bright-field microscopes are still prevalent in laboratories; however, they are limited by their inability to image transparent objects without labeling.

This limitation is due to an inherent attribute of transparent samples: they weakly scatter light, producing a negligible scattered field amplitude compared to that of the illuminating (i.e., unscattered) field. When the scattered field amplitude is negligible, the total light transmitted through the object, known as the foreground, is approximated by the illuminating field [2]. Variation between the amplitudes of the foreground and the illuminating field provides contrast, rendering objects visible under a bright-field microscope. While opaque objects naturally provide this variation, transparent ones do not. As a result, the latter appear invisible unless labeled.

In the early twentieth century, transparent specimens were stained to increase the scattered field amplitude and, thus, provide contrast between a sample and its background; however, later in the 1930's, Fritz Zernike created a new technique known as phase contrast microscopy, eliminating the need to label cells before imaging. Zernike realized that although the scattered field of a transparent object has negligible amplitude, it intrinsically exhibits a significant shift in phase [3, 4]. Note that while amplitude shifts are detectable by the human eye, phase shifts are not.

Zernike discovered that transparent objects produce a -90° phase shift in the scattered field. For this reason, phase contrast microscopes shift the phase of the unscattered field by -90° . This enables constructive interference, which produces increased sample brightness [5]. After a phase shift, the unscattered amplitude is reduced so that the scattered field has greater impact on the foreground. This final step creates higher contrast between the phase object and its surroundings, rendering it visible through an eyepiece without labeling. See Fig. 1 for a typical phase image.

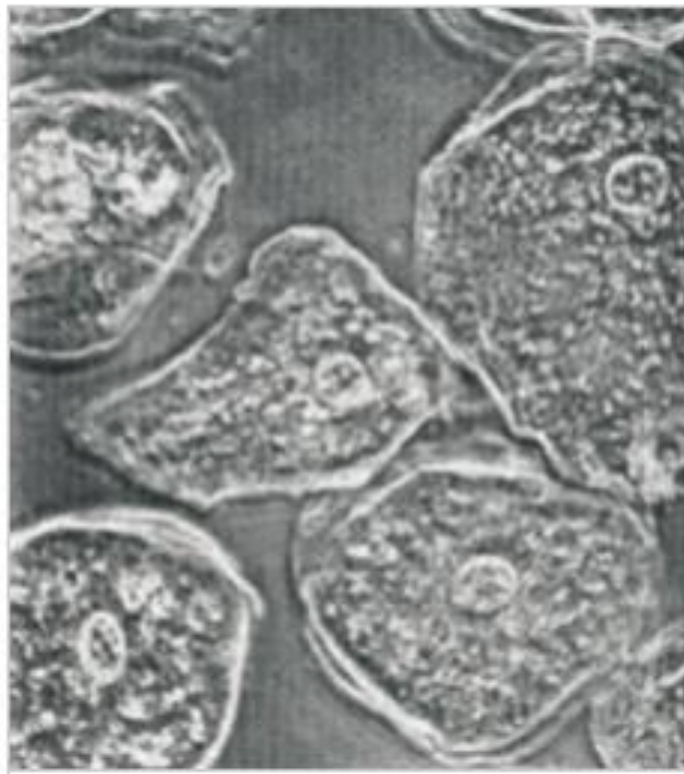


Figure 1. Phase contrast image of epithelial cells from the mouth produced in 1947 [6].

1.1 QPI Techniques

With phase contrast microscopy, a change in the phase of the scattered field is converted to an intensity change, providing qualitative information regarding the topology of opaque and transparent samples [7]. The more recent invention of quantitative phase imaging (QPI) provides both qualitative and quantitative data. QPI integrates a detector at the image plane rather than an eyepiece. As a result, quantitative field intensity measurements can be made and computer algorithms can be used to determine the actual height and/or refractive index variation across a sample [8]. Because the phase of a field (as opposed to its amplitude) is more sensitive to structural changes in an object, phase imaging is advantageous even with opaque samples [9].

Many quantitative phase imaging systems, including the diffraction phase microscope (DPM) discussed in this thesis, use interferometers for phase determination. This is necessary because detectors are only capable of measuring field intensity. To extract phase from a given intensity, one can implement the following interferometric technique: 1) Split a source wave into two waves. 2) Delay the distance that one wave travels with respect to the other. 3) Recombine the two waves at the image plane. 4) Use the intensity equation (discussed in Section 3) to extract the phase.

Traditionally, the phase of the scattered field (i.e., the object beam) is then compared to that of the unscattered field (i.e., reference beam) for phase change measurements. Variation in the optical path lengths of the two beams produces a fringe pattern in the detector plane. The fringe pattern is examined for horizontal shifts, which correspond to a change in height across a sample (see Fig. 2) [9]. DPM functionality is based on conventional interferometers but is slightly different because both of its beams interact with

the sample. The beams are copies of a single image; however, they do have different optical path lengths and, thus, produce interference fringes in the detector plane. DPM mechanisms are further discussed in Section 3.

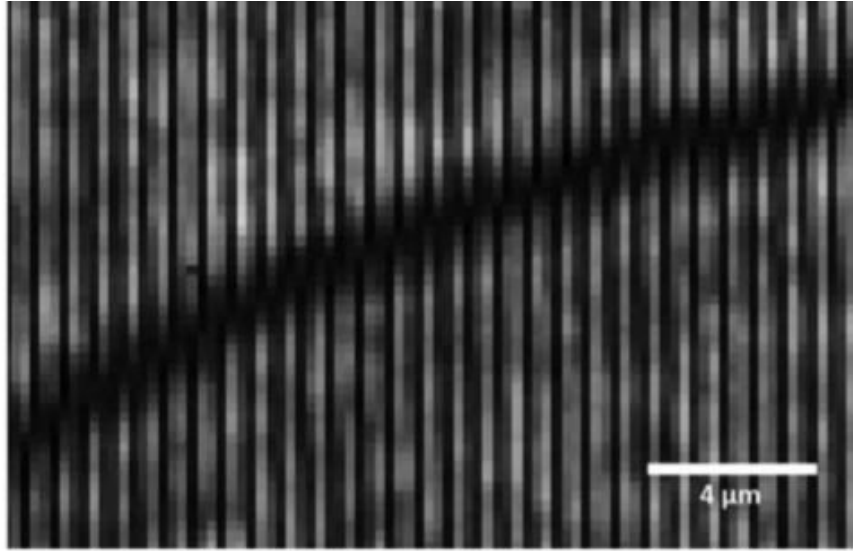


Figure 2. DPM image showcasing fringes associated with the edge of a micropillar. The horizontal shift in fringes corresponds to a 135-nm change in height from the top of the structure to its base [9].

1.2 Diffraction Phase Microscopy Advantages

Diffraction phase microscopy has been prevalent in the past decade and used for many applications in electrical engineering, biology, materials science, and bioengineering. Notable DPM applications include the observation of semiconductor wafer defects, red blood cell mechanics, live neurons, wet chemical etching, material expansion, and material deformation [9] – [11]. The primary advantages of DPM over other methods such as transport of intensity (TIE) and Fourier ptychography include its lower spatial and temporal noise, ability for direct non-iterative phase retrieval, and reduced sensitivity to measurement error or boundary conditions.

2. Thesis Proposal

The author proposes scaling down a macro-scale DPM system to implement a Mach-Zehnder-based interferometer on-chip. Though various interferometric sensors have been fabricated on-chip, none have included a micro-scale DPM system explicitly. DPM on-chip maintains the numerous advantages of macro-scale DPM, including the ability to 1) cancel noise associated with standard interferometry setups due to vibrations and air flow, 2) noninvasively image opaque and transparent samples, and 3) execute fast image acquisition limited only by the specifications of the charge-coupled device (CCD) or the complementary metal oxide semiconductor (CMOS) camera being used [12].

DPM on-chip introduces additional advantages, such as its space-saving ability. A standard macro-scale DPM system can span several feet in a laboratory. Fabricating key components on-chip (i.e., on the scale of millimeters) reduces the overall size of the system significantly and unlocks the possibility of mass-produced, portable DPM systems that could be integrated as a mobile phone accessory. A second advantage of DPM on-chip includes the reduction in material consumption and, thus, the cost of the optical system. Fabricating both lenses as Fresnel lenses results in lower material consumption than a classical lens. The third benefit of the system is the potential reduction in alignment error. It is known that engineers devote significant time to optical alignment because each integrated optic can introduce additional error. An on-chip device with self-aligned elements will significantly reduce alignment time as well as alignment error for those replicating the system.

After summarizing design constraint derivations for the macro-scale system created by Basanta Bhaduri et al. [9], the author will present optimized parameters for DPM on-chip.

An explanation detailing why Fresnel lenses are specialized cases of Fresnel phase plates will also be presented. Fabrication techniques for the Fresnel lens and the pinhole filter are then discussed. The author concludes this thesis by discussing the testing, applications, and proposed future work for the on-chip system.

3. DPM Design Criteria

A DPM system is composed of a laser, a conventional microscope, a CCD or CMOS camera, and four unique components including: a blazed grating, two lenses, and a pinhole (see Fig. 3). The wavelength of the laser depends on the application. It should not affect the behavior of samples in their natural environments (e.g., UV light is typically avoided when observing live cells due to its ability to damage DNA). The conventional microscope is selected for its internal optics (i.e., numerical aperture, transverse resolution, and magnification). Sections 3.3 – 3.8 detail the relationship between the specifications of the laser, microscope, camera, and key DPM components.

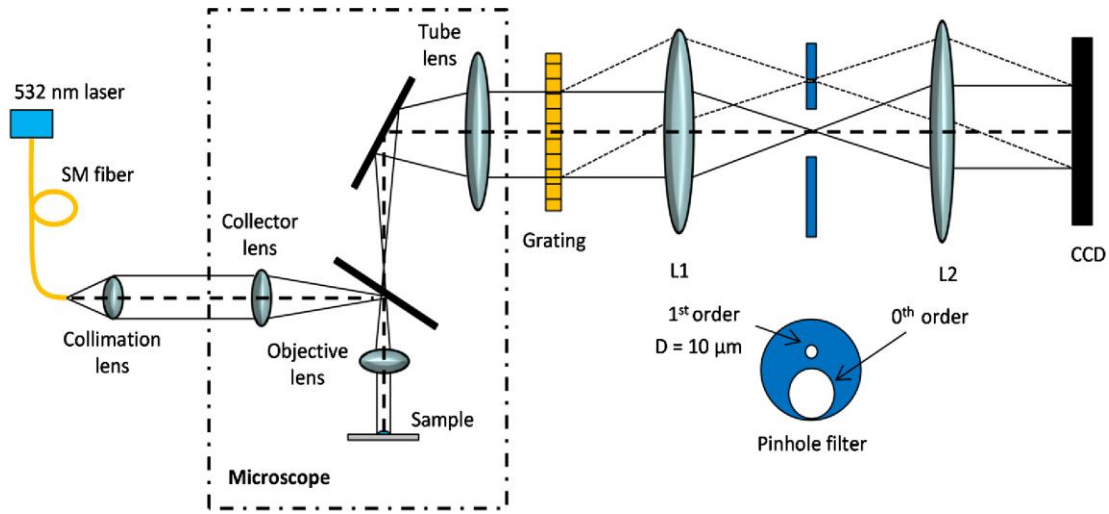


Figure 3. DPM in reflection mode. The image output by a standard microscope is sent through DPM key components: grating, lenses, pinhole filter, and aperture. An interferogram appears on the CCD or CMOS camera [9].

The blazed grating creates multiple copies of the microscope image that travel at various angles. These angles, θ_m , are governed by the grating equation below, which assumes normal incidence:

$$\Lambda \sin\theta_m = m\lambda \quad (1)$$

where Λ is the grating period, and m is the order of diffraction. Based on this equation, one can see that various wavelengths of light will diffract at different angles. For this proposal, only monochromatic light will be analyzed.

The 0th and +1 order beams are the only ones of importance when forming a DPM interferogram. Although the grating creates additional image copies, other orders are intentionally blocked in the Fourier plane. The 0th order beam passes freely through an aperture in the Fourier plane while the +1 order beam (i.e., the reference beam) passes through a pinhole that filters out higher spatial frequencies to create a uniform reference intensity. As a result, the 0th order beam contains the original image content, and the +1 order contains only DC information. The pinhole also serves to reduce first order intensity so that it is closer to that of the 0th order. This is necessary because a blazed grating significantly increases the diffraction efficiency of light travelling in the +1 order while simultaneously reducing that of the 0th order. For fringes to appear uniform in the camera plane, the intensity of both orders should be approximately equal.

3.1 Intensity Equation in Camera Plane

When designing a macro-scale DPM system, one must consider the following design constraints: 1) grating period, 2) minimum 4f magnification, 3) pinhole spacing in the Fourier plane, 4) numerical aperture for both lenses in the 4f system, and 5) pinhole diameter. One should also ensure that the coupling ratio is minimal to properly reconstruct the phase. The author proposes that the aforementioned constraints can also be applied to

a micro-scale DPM system. During the discussion of derivations, numerical values for a DPM on-chip system that are feasible to fabricate will be presented.

As mentioned in Section 1.1, DPM is an interferometer that uses an interference equation to extract the phase of a sample. Let us examine how the field at the image plane of the conventional microscope is modified as it traverses through the DPM system. The following derivations are summarized from [9].

As shown in Fig. 3, the grating is placed at the image plane to produce multiple copies of the image. The 0th and +1 order beams are of interest for this system, as the others are later blocked in the Fourier plane. For this reason, U_0 and U_1 are used to describe the field amplitudes of the 0th and +1 order, respectively. The field at the grating plane is:

$$U(x, y) = U_0(x, y) + U_1(x, y)e^{i\beta x}, \quad (2)$$

where $\beta \equiv \frac{2\pi}{\Lambda}$ is the modulation frequency due to the grating. The 0th and +1 orders of light propagate through lens 1 of the system, which causes a Fourier transform of the field.

$$\tilde{U}(k_x, k_y) = \tilde{U}_0(k_x, k_y) + \tilde{U}_1(k_x - \beta, k_y), \quad (3)$$

where $\tilde{U}(k_x, k_y)$ is the Fourier transform of $U(x, y)$, $k_x = \frac{2\pi x_1}{\lambda f_1}$, and $k_y = \frac{2\pi y_1}{\lambda f_1}$. As light travels through the spatial filter placed at the Fourier plane, which allows full passage of the 0th order and only DC passage for the +1 order, U_1 undergoes convolution. This is represented by multiplication with the delta function. The field becomes:

$$\tilde{U}(k_x, k_y) = \tilde{U}_0(k_x, k_y) + \tilde{U}_1(0,0) \delta(k_x - \beta, k_y), \quad (4)$$

The field is then Fourier transformed by another lens resulting in the following magnified, inverted field at the camera plane:

$$U_{CP}(x, y) = \frac{1}{|\frac{2\pi}{\lambda f_1}|} [U_0(x', y') + U_1(0,0)e^{i\beta x/M_{4f}}], \quad (5)$$

where $x' = -\frac{x}{M_{4f}}$, $y' = -\frac{y}{M_{4f}}$, and $M_{4f} \equiv -\frac{f_2}{f_1}$. Note that M_{4f} defines the magnification of the DPM portion of the system. Allowing U_0 and U_1 to be expressed as phasors, the authors in [9] expressed the intensity equation as follows:

$$\begin{aligned} I(x', y') &= U_{CP}(x, y)U_{CP}^*(x, y) \\ &= I_0(x', y') + I_1(x', y') + 2\sqrt{I_0(x', y')I_1} \cos(\beta x' + \Delta\phi), \end{aligned} \quad (6)$$

where I_0 and I_1 are the intensities of the 0th and +1 order beams, respectively, and $\Delta\phi = \phi_0(x', y') - \phi_1$ represents the change in phase caused by the sample. Knowing this phase value allows one to compute the height across a sample because the phase relates to height in two simple equations: one for reflection mode (Equation 7a) and another for transmission mode (Equation 7b):

$$h(x, y) = \frac{\varphi(x, y)\lambda_0}{4\pi\Delta n} \quad (7a)$$

$$h(x, y) = \frac{\varphi(x, y)\lambda_0}{2\pi\Delta n}, \quad (7b)$$

where λ_0 is the wavelength of the laser and Δn is the difference in the refractive index between the sample and its environment.

The microscope system defines the transverse resolution of the DPM system. Additionally, the grating period must be chosen so that it does not reduce the resolution quality provided by the microscope. The maximum grating period allowed is determined by light interaction in the Fourier plane. Taking the intensity of the beams in the camera plane and converting it to its spatial frequency counterpart, authors in [9] determined:

$$\begin{aligned} \tilde{I}(k_x, k_y) = & \tilde{U}_0(k_x, k_y) \vee \tilde{U}_0^*(-k_x, -k_y) + |U_1|^2 \delta(k_x, k_y) + \\ & \tilde{U}_0(k_x, k_y) U_1^* \vee \delta(k_x - \beta, k_y) + \tilde{U}_0^*(-k_x, -k_y) U_1 \vee \delta(k_x + \beta, k_y), \end{aligned} \quad (8)$$

where $\vee$ represents the convolution operator. Each term in Equation 8 is physically represented in the Fourier plane as a circle with a specific radius, except for the second term, $|U_1|^2 \delta(k_x, k_y)$, which represents the DC component of the reference beam and, thus, appears as a spot (see Fig. 4). The spacing of these lobes in the Fourier plane determines whether the interferogram is properly reconstructed. The first term in Equation 8 represents the central lobe with radius $2k_0 \text{NA}_{\text{obj}}$. The third and fourth terms represent the circles with radius $k_0 \text{NA}_{\text{obj}}$ that are shifted to the right and left, respectively, of the central lobe.

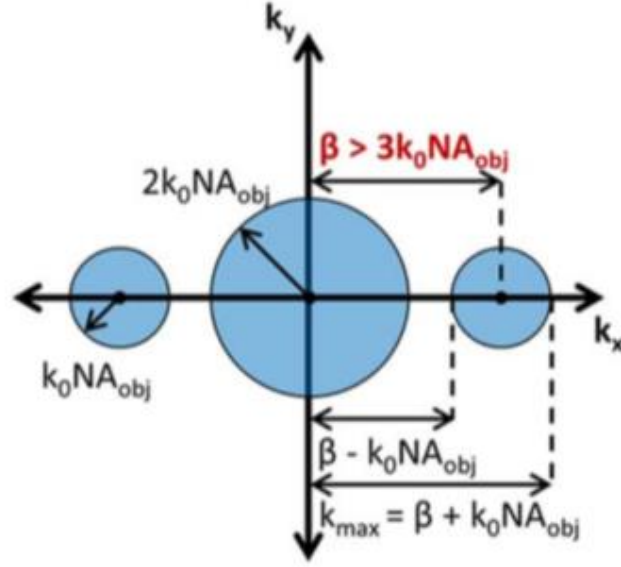


Figure 4. Schematic showing the Fourier transform of the camera image. Each of the lobes in addition to a point representing the DC term at the origin are represented as terms in Equation 8 [9].

3.2 Phase Retrieval

One must implement a phase reconstruction algorithm to successfully retrieve the phase from the interferogram captured by the camera. Although the author will use an algorithm that was already developed, the process of how the algorithm functions will briefly be discussed here. A calibration (i.e., background) image is taken from a flat region on the sample. Then, a Fourier transform is applied. A bandpass filter is used to select the spatially modulated signal represented by the lobe on the right side and optionally shift it to the center of the Fourier plane. This process is then repeated for the region of interest on a sample. An inverse Fourier transform of both the background and the image occurs before the background is subtracted from the image via division of their associated complex fields. Lastly, phase unwrapping algorithms are applied to retrieve the absolute phase. This is

necessary because wrapped phase images can occur when the optical path length difference is greater than one wavelength [13]. By inserting the absolute phase into Equation 7a and Equation 7b, one can then determine the height across a sample.

3.3 Design Constraint 1: Grating Period

The positions of the smaller lobes with respect to the central lobe are determined by the grating period. To ensure that they do not overlap with the central lobe, the following constraint is placed on modulation frequency in the sample plane, $\beta = \left(\frac{2\pi}{\Lambda}\right)M_{obj}$:

$$\beta \geq 3k_0NA_{obj}, \quad (9)$$

where k_0 is the wavenumber and NA_{obj} is the numerical aperture of the microscope objective. Note that β is precisely the distance between the centers of the central lobe and the side lobe. As a result, the constraint on the grating period becomes:

$$\Lambda \leq \frac{\lambda M_{obj}}{3NA_{obj}} \quad (10)$$

Using a system with $\lambda = 405$ nm, $M_{obj} = 5X$, and $NA_{obj} = 0.8$ for DPM on-chip Design #1, the grating period cannot exceed $0.84375 \mu\text{m}$ and so a reasonable and commercially available choice is a 1200 line per mm grating ($\Lambda = 0.833 \mu\text{m}$). For Design #2, which is for

$\lambda = 633 \text{ nm}$, $M_{obj} = 20X$, and $NA_{obj} = 0.8$, the grating period cannot exceed $5.275 \text{ }\mu\text{m}$ and so the corresponding choice is a 300 line per mm grating ($\Lambda = 3.33 \text{ }\mu\text{m}$).

3.4 Design Constraint 2: 4f Magnification

In addition to selecting an appropriate grating period for proper signal sampling, one must also consider the sampling frequency of pixels in the camera. The authors in [9] defined $k_{max} \equiv \beta + k_0 NA_{obj}$. Using this definition and the Nyquist criteria, they determined the constraint on pixel sampling frequency, k_s , to be:

$$k_s \geq 2k_{max}, \quad (11)$$

where $k_s = \left(\frac{2\pi}{a}\right) M_{obj} |M_{4f}|$ can be substituted into the Equation 11. This leads to the second design constraint, which determines the minimum 4f magnification for a given grating period and pixel sampling frequency. Note that variable a represents pixel size. The result is:

$$|M_{4f}| \geq 2a \left[\frac{1}{\Lambda} + \frac{1}{\lambda} \frac{NA_{obj}}{M_{obj}} \right] \quad (12)$$

3.5 Design Constraint 3: Pinhole and Aperture Spacing

The spacing between the aperture that allows full passage of the 0th order beam and the pinhole that filters the +1 order beam is determined by geometry and the grating equation

(Equation 1). Because lens 1 is placed a distance equal to its focal length from the grating, one can relate the separation distance between the two beams, Δx , to the focal length of the lens and the diffraction angle of the grating.

$$\tan(\theta_m) = \frac{\Delta x}{f_1} \quad (13)$$

Note that for small angles, which occur in a DPM system, $\tan(\theta) \approx \sin(\theta) \approx \theta$. As a result, one can equate Equation 13 to the grating equation and find that:

$$\Delta x = \frac{f_1 \lambda}{\Lambda} \quad (14)$$

For DPM on-chip Design #1, $\Delta x = 1.215$ mm. For Design #2, $\Delta x = 0.587$ mm.

3.6 Design Constraint 4: Numerical Aperture of Lens 1

To ensure that both beams pass through lens 1 and also properly through the aperture and pinhole, an appropriate numerical aperture for lens 1 must be chosen. This constraint is based on the pinhole spacing and light collected by the objective.

$$NA_{L1} \geq \frac{\lambda}{\Lambda} + \frac{NA_{obj}}{M_{obj}} \quad (15)$$

3.7 Design Constraint 5: Pinhole Diameter

The size of the aperture should be large enough for the 0th order beam to fully pass. The size of the pinhole has more restriction and is chosen to produce a uniform diffraction pattern for the reference beam with approximately the same intensity as the 0th order. Therefore, pinhole size directly affects fringe visibility. When a plane wave passes through a pinhole of diameter D , the resulting diffraction pattern (Equation 16) is proportional to the square of Bessel function, J_1 .

$$I(x, y) = I_0 \left[\frac{2J_1\left(\frac{\pi D \rho}{\lambda f_2}\right)}{\frac{\pi D \rho}{\lambda f_2}} \right]^2, \quad (16)$$

where I_0 is the peak intensity, and f_2 is the focal length of lens 2. Also, $\rho = \sqrt{x^2 + y^2}$ is the radius of the central lobe of the Bessel function. By taking the argument of the Bessel function and equating it to the first zero of the function (i.e., 3.83), the authors in [9] solved for the radius of the central lobe:

$$\rho = 3.83 \frac{\lambda f_2}{\pi D} = 1.22 \frac{\lambda f_2}{D} \quad (17)$$

For a camera with $m \times n$ pixels, the length of the diagonal is

$$d = a\sqrt{m^2 + n^2}. \quad (18)$$

Because the radius of the central lobe should be much greater than the diagonal of the camera for a uniform reference signal across the field of view (FOV), one can determine the maximum pinhole size:

$$\rho = 1.22 \frac{\lambda f_2}{D} \geq d \rightarrow D \leq 1.22 \left(\frac{\lambda f_2}{d} \right) \quad (19)$$

To ensure that the central lobe of the Bessel function is greater than the diagonal of the camera, the authors in [9] chose to multiply the diagonal by a factor $\gamma/2$. As a result, Equation 19 becomes:

$$\rho = 1.22 \frac{\lambda f_2}{D} \geq \left(\frac{\gamma}{2} \right) d \rightarrow D \leq 2.44 \left(\frac{\lambda f_2}{\gamma d} \right). \quad (20)$$

For DPM on-chip Design #1, $D = 2.34 \mu\text{m}$. For Design #2, $D = 1 \mu\text{m}$.

3.8 Design Constraint 6: Numerical Aperture of Lens 2

The final DPM design constraint determines the minimum numerical aperture for lens 2 and is

$$NA_{L2} \geq \frac{\lambda}{|M_{4f}|\Lambda} + \frac{1.22\lambda}{\gamma D}. \quad (21)$$

The selected numerical aperture for lens 2 of DPM on-chip Design #1 is 0.345. For Design #2, it is 0.532.

4. DPM On-Chip Overview

Microsoft Excel was utilized to compare various on-chip element combinations while also ensuring that the six previously discussed designed constraints were met. Two on-chip designs were developed. Optimized parameters for Design #1 ($\lambda = 405$ nm) were initially determined; they are summarized in Table 1. During fabrication, we improved the design and created Design #2, where $\lambda = 633$ nm (Table 2). Design #2 uses values for the microscope objective's magnification and numerical aperture that are more commercially available. Further discussion regarding the change is given in Section 8.

Table 1. Optimized DPM on-chip parameters: Design #1. Using design constraints originating from macro-scale DPM, key components were reduced to the micro-scale. With Design #1, the wavelength is set to 405 nm and the objective to 5X / 0.8. All other parameters are updated accordingly.

<u>Parameter Name</u>	<u>Abbreviation</u>	<u>Optimized Value</u>
Wavelength	λ	0.405 μm
Magnification of Microscope Objective	M_{obj}	5
Numerical Aperture of Microscope Objective	NA_{obj}	0.8
Grating Period	Λ	0.8333 μm
Focal Length of Lens 1	f_1	2.5 mm
Diameter of Lens 1	D_{L1}	4.25 mm
Numerical Aperture of Lens 1	NA_1	0.648
Pinhole Filter Spacing	Δx	1.215 mm
Focal Length of Lens 2	f_2	10.336 mm
Diameter of Lens 2	D_{L2}	7.6 mm
Numerical Aperture of Lens 2	NA_2	0.345
Diameter of Pinhole	D	2.34 μm
Gamma	γ	3.6
Magnification of 4f System	M_{4f}	4.13
Pixel Width	a	1.25 μm

Table 2. Optimized DPM on-chip parameters: Design #2. Using design constraints originating from macro-scale DPM, key components were reduced to the micro-scale. With Design #2, the wavelength is set to 633 nm, objective to 20X / 0.8, and focal lengths to 3 mm. All other parameters are updated accordingly.

<u>Parameter Name</u>	<u>Abbreviation</u>	<u>Optimized Value</u>
Wavelength	λ	0.633 μm
Magnification of Microscope Objective	M_{obj}	20
Numerical Aperture of Microscope Objective	NA_{obj}	0.8
Grating Period	Λ	3.33 μm
Focal Length of Lens 1	f_1	3.0 mm
Diameter of Lens 1	D_{L1}	1.44 mm
Numerical Aperture of Lens 1	NA_1	0.233
Pinhole Filter Spacing	Δx	0.570 mm
Focal Length of Lens 2	f_2	3.0 mm
Diameter of Lens 2	D_{L2}	3.77 mm
Numerical Aperture of Lens 2	NA_2	0.532
Diameter of Pinhole	D	1 μm
Gamma	γ	3.6
Magnification of 4f System	M_{4f}	1.0
Pixel Width	a	1.25 μm

Figure 5 shows a schematic of the four key components of Design #1. Initially, lens 1, the pinhole, and the aperture were to form a single substrate. Lens 2 and the grating were to remain separate. During fabrication, however, the design evolved so that all the aforementioned components are combined instead as shown in Fig. 6. The diagonal FOV of a DPM system is an important attribute to note and is computed as

$$FOV_{diagonal} = \frac{a\sqrt{m^2+n^2}}{M_{obj}|M_{4f}|}. \quad (22)$$

The calculated diagonal FOV is 371 μm for Design #1 and 480 μm for Design #2 when a sample is imaged with an Amscope MU1803 CMOS camera. The camera contains a 6.14 mm by 4.61 mm sensor; it has a pixel size of 1.25 μm . If we were to use the entire area of

the camera, DPM constraints would be more challenging to implement. In particular, the pinhole diameter would reach unattainably small dimensions. Therefore, we opted to reduce the number of pixels used via image cropping so that the FOV would equal $58\text{ }\mu\text{m}$ for Design #1 and $41\text{ }\mu\text{m}$ for Design #2.

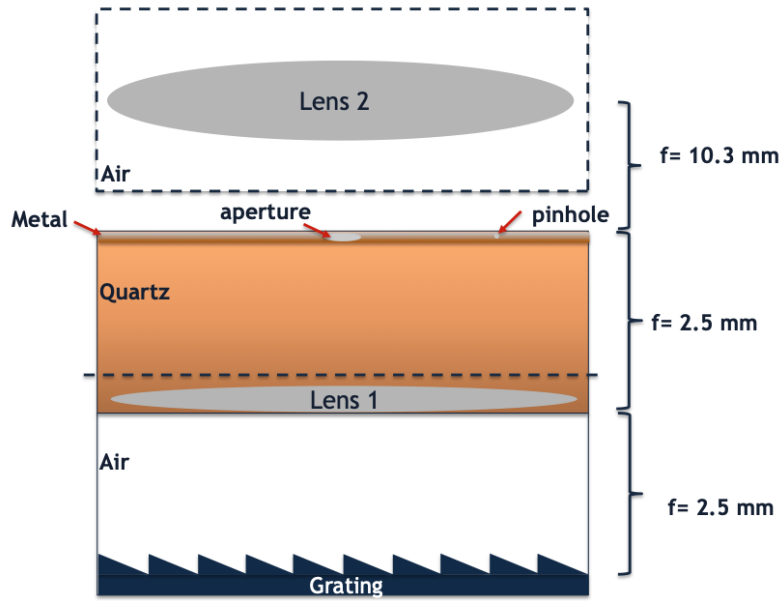


Figure 5. Schematic of DPM on-chip Design #1 prototype. In the original design, lens 1, the pinhole, and the aperture were to compose one substrate. The grating would be a commercial device. Lens 2 would exist separately. This design was later updated.

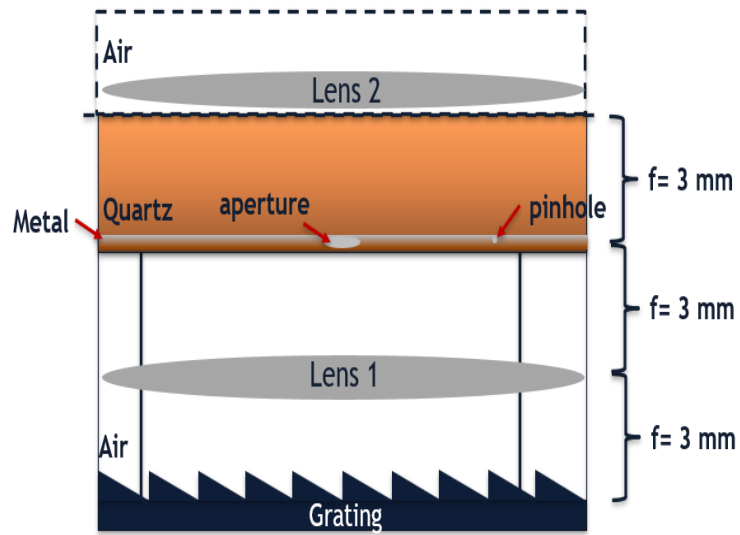


Figure 6. Schematic of DPM on-chip Design #2 prototype. In the modified design, the pinhole, aperture, and lens 2 compose one substrate. The grating and lens 1 would compose another. The latter two would be commercial devices.

5. Simulation Results

The shape of the grating profile affects the diffraction efficiencies for each order of light [14]. Because a blazed grating, which diffracts light mostly into the +1 order, was chosen for [9], it will also be used for DPM on-chip. If desired, the effect of varying profile geometry can be explored using COMSOL during future work.

When lab access and instrument training were limited during the first year of the pandemic, the author began to use COMSOL for simulations of key DPM on-chip components including the grating and Fresnel lenses. The author began simulating scenarios for which known solutions exist, including the interaction of a plane wave incident on a glass slab (see Fig. 7) and a blazed grating. In both cases, it was necessary to select the appropriate dimensions and geometries for the object of interest (i.e., the slab or grating). The effects of perfectly matched layers (PMLs), which are fundamental in electromagnetic simulations, were explored. For the case of the grating, appropriate boundary conditions were also implemented. Simulation results are shown below for Design #1. COMSOL documentation and tutorials proved very useful in helping the author develop simulation skills. Once lab facilities re-opened, the author focused efforts on fabricating samples and building the experiment in the lab rather than executing simulations of the Fresnel lens or simulations of the optics for Design #2, especially because the trends for dimensional scaling are known.

5.1 Glass Slab Simulation

Reflectance and transmittance values were observed for a glass slab simulation. Because an analytical solution for this scenario is known, it was used to compare simulated results (see Figs. 8 and 9).

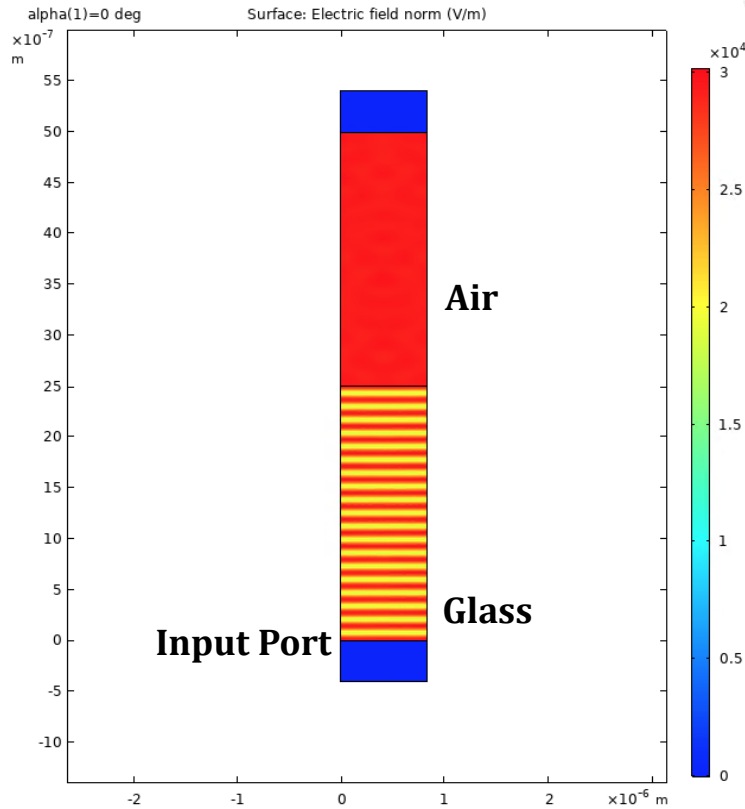


Figure 7. Total field for plane wave illumination at normal incidence into glass and air regions. The power of the incident field is set to 1 W. Perfectly matched layers have the same width as the slab $w = 833$ nm and a length set equal to 1λ (i.e., 405 nm).

As expected, the reflection and transmission for a plane wave incident on the glass slab with normal incidence will have a reflectance of $\sim 5\%$ and transmittance of $\sim 95\%$.

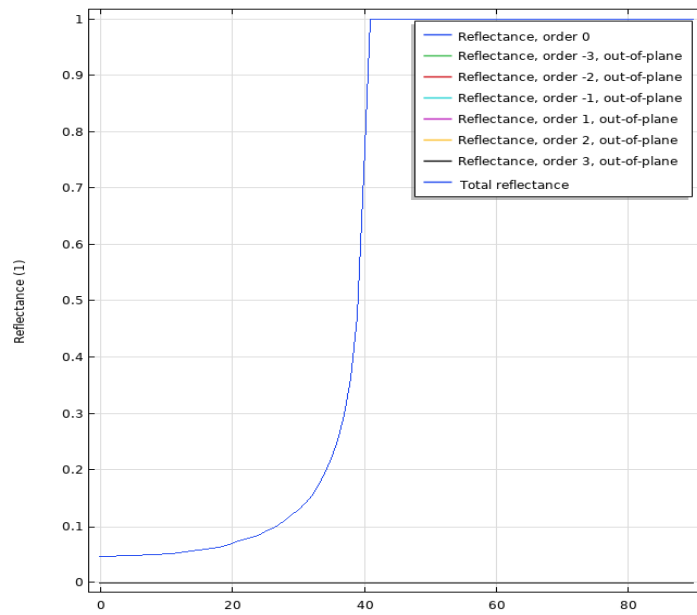


Figure 8. Reflectance for glass slab simulation. Only the 0th order of light reflects for this case with a reflectance of approximately 5%.

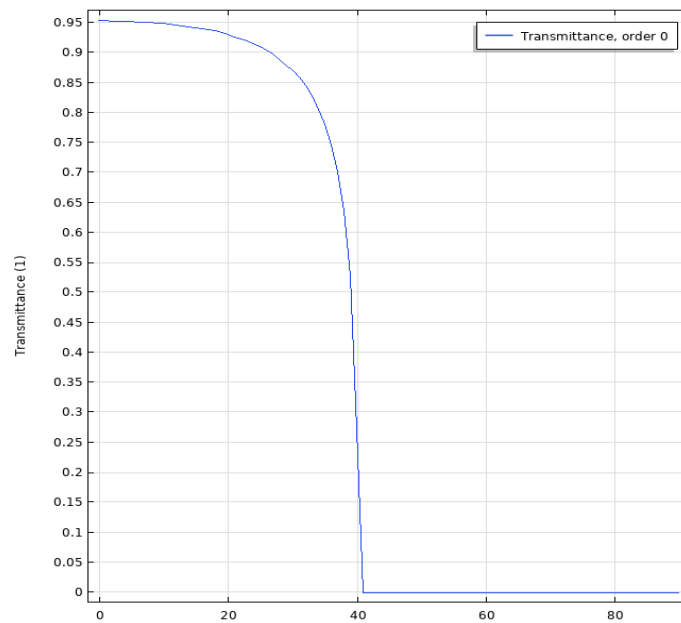


Figure 9. Transmission coefficient for glass slab simulation. Approximately 95% of the light passes through the glass slab.

5.2 The Perfectly Matched Layer

The perfectly matched layer (PML) is an absorbing boundary condition used in numerical simulations to ensure that its impedance is perfectly matched to the region of interest in a simulation. Waves that enter this lossy region are prevented from reflecting because the impedance is matched: outgoing waves are absorbed. Simulations showed that PML thickness directly affected the total field magnitude. The standard is to set its thickness as an integer multiple of the wavelength. To evaluate whether a PML with thickness equal to one wavelength was sufficient for a glass slab or grating simulation, the Poynting vector was calculated (see Figs. 10 and 11). Examining the direction of energy flow showed that reflections did not occur at the boundaries of the regions of interest and thus the PML thickness was sufficient.

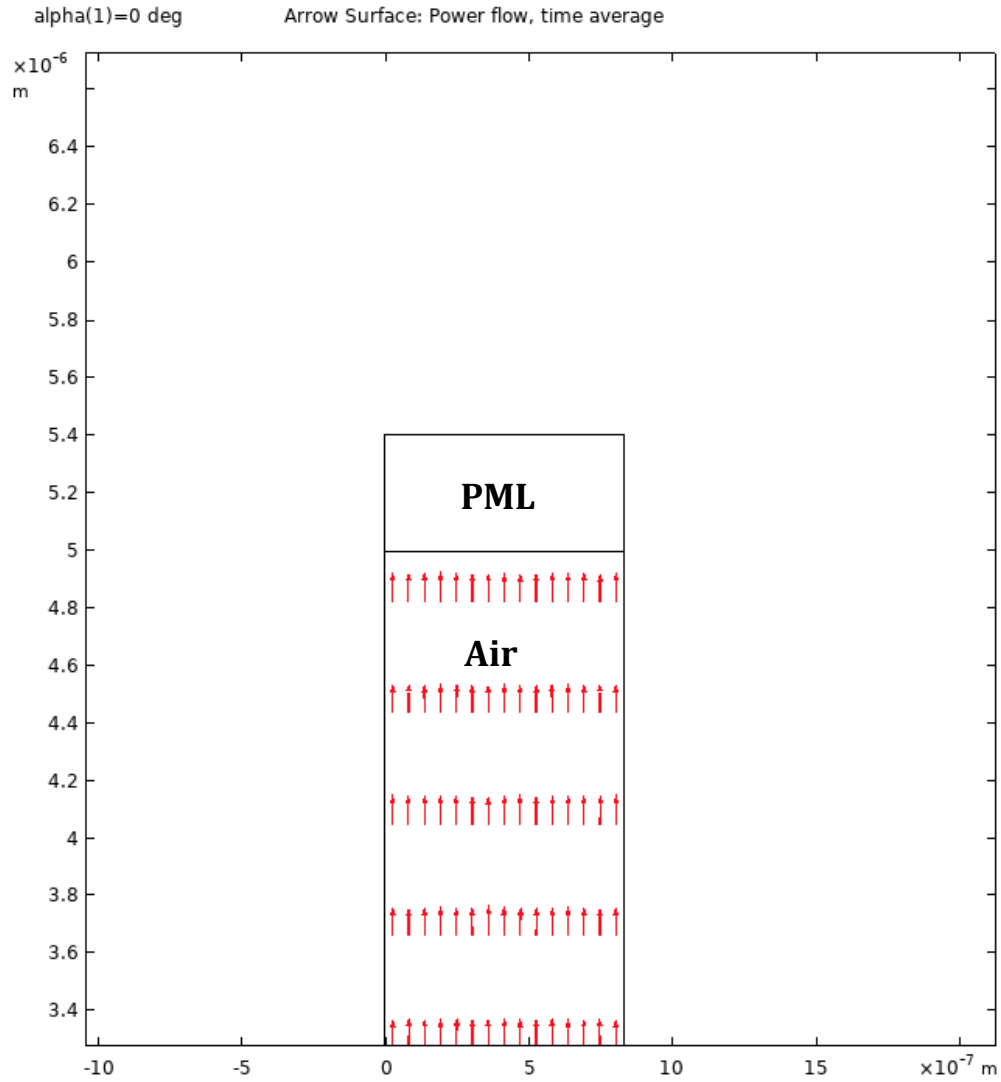


Figure 10. Poynting Vector at PML/air interface. PML thickness equals 1λ . COMSOL-defined variables assisted in plotting the arrow surface. No power is reflected at the edges of the simulation region.

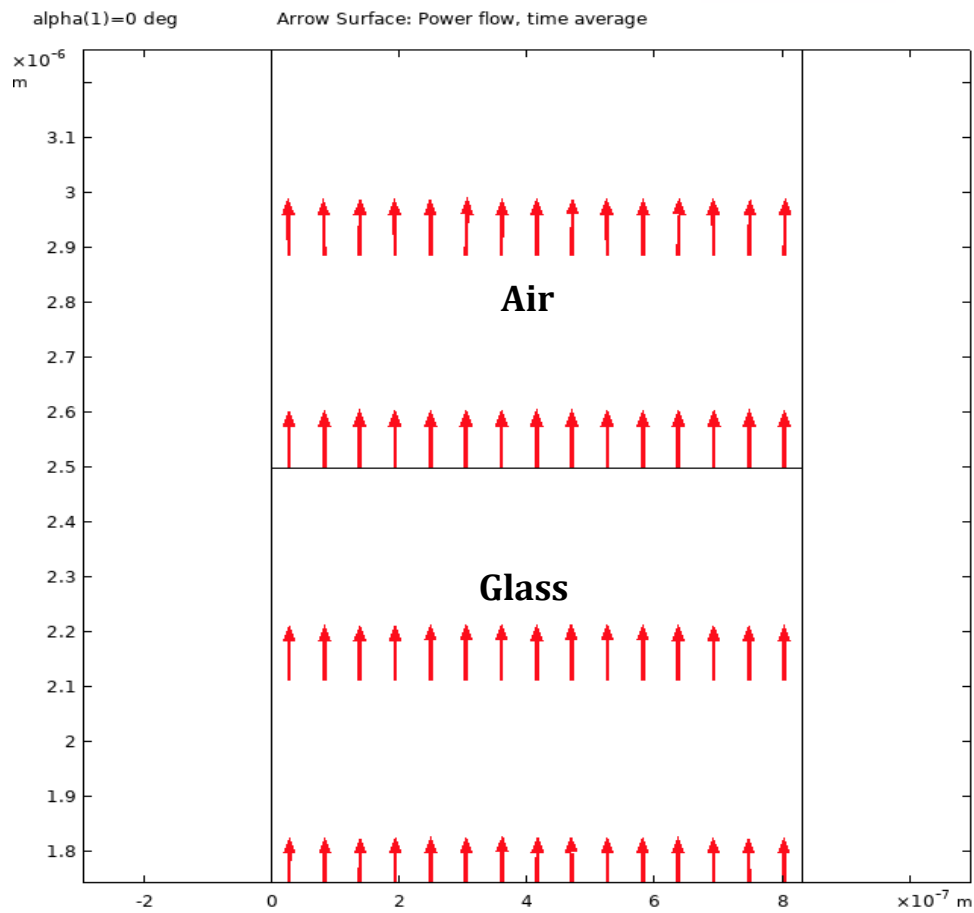


Figure 11. Poynting Vector at air/glass interface. PML thickness equals 1λ . COMSOL-defined variables assisted in plotting the arrow surface. This demonstrates that power flows in the direction away from the input port.

5.3 Binary Diffraction Grating Simulation

Following simulations of a glass slab, additional ones were performed on a binary grating and a blazed grating. Periodic boundary conditions were applied to a unit cell to mimic an infinite grating. To verify that the simulation of the binary grating without PMLs was correct (see Fig. 12), the author used a grating period and wavelength suggested by COMSOL in order to compare the results to those obtained by COMSOL engineers. A second simulation was performed to determine the effect of adding PMLs to the simulation region (see Fig. 13). Note that COMSOL engineers did not use PMLs.

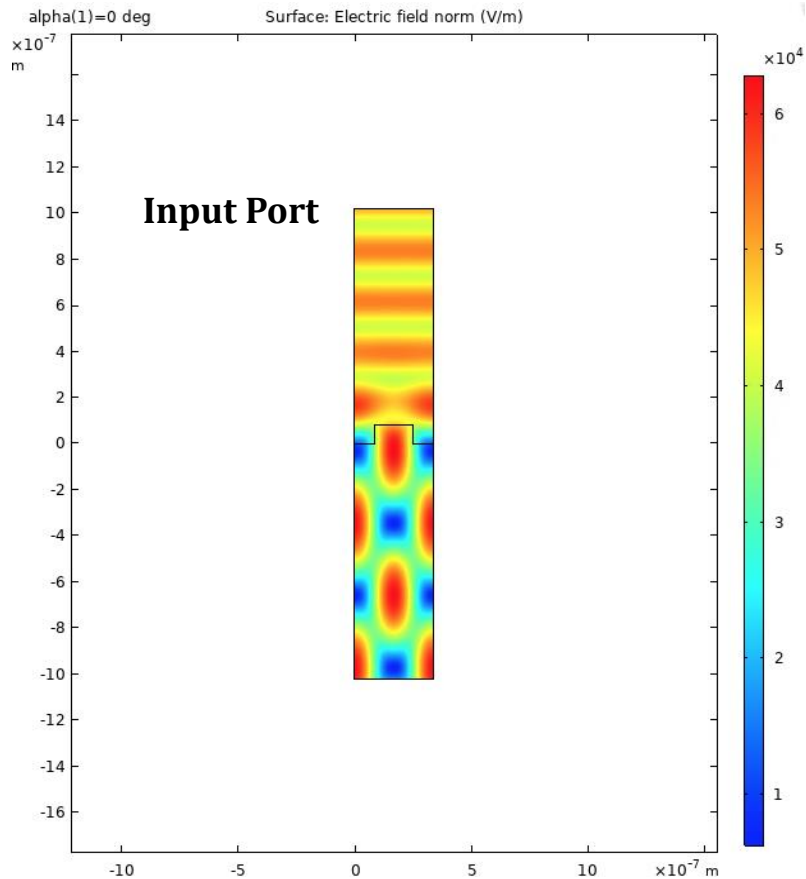


Figure 12. Total field for diffraction grating without PML. Light at normal incidence. The range of the magnitude associated with this case slightly varies from the case with PML present.

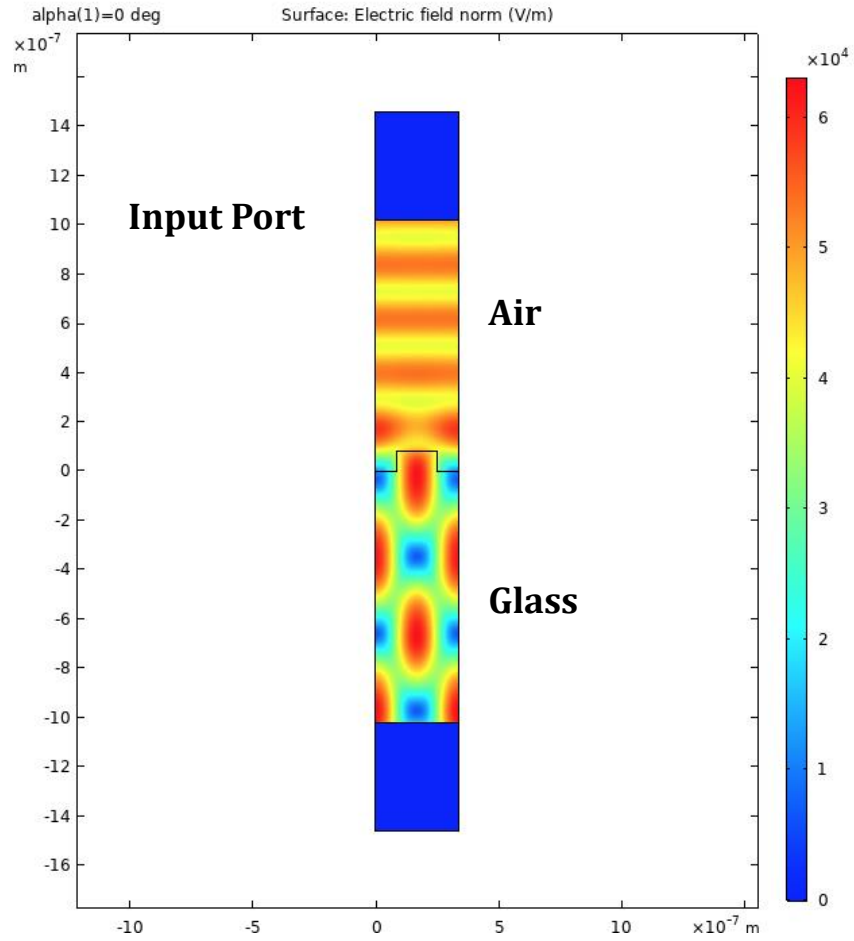


Figure 13. Total field for diffraction grating with PMLs. PMLs are marked by blue and are on the exterior of the region of interest. Grating constant $\Lambda = 340$ nm. $\lambda = 441$ nm.

Although the presence of PMLs did not affect the binary grating when a plane wave approached at normal incidence, significant changes to the total field magnitude are present when light approaches at an angle (see Figs. 14 and 15).

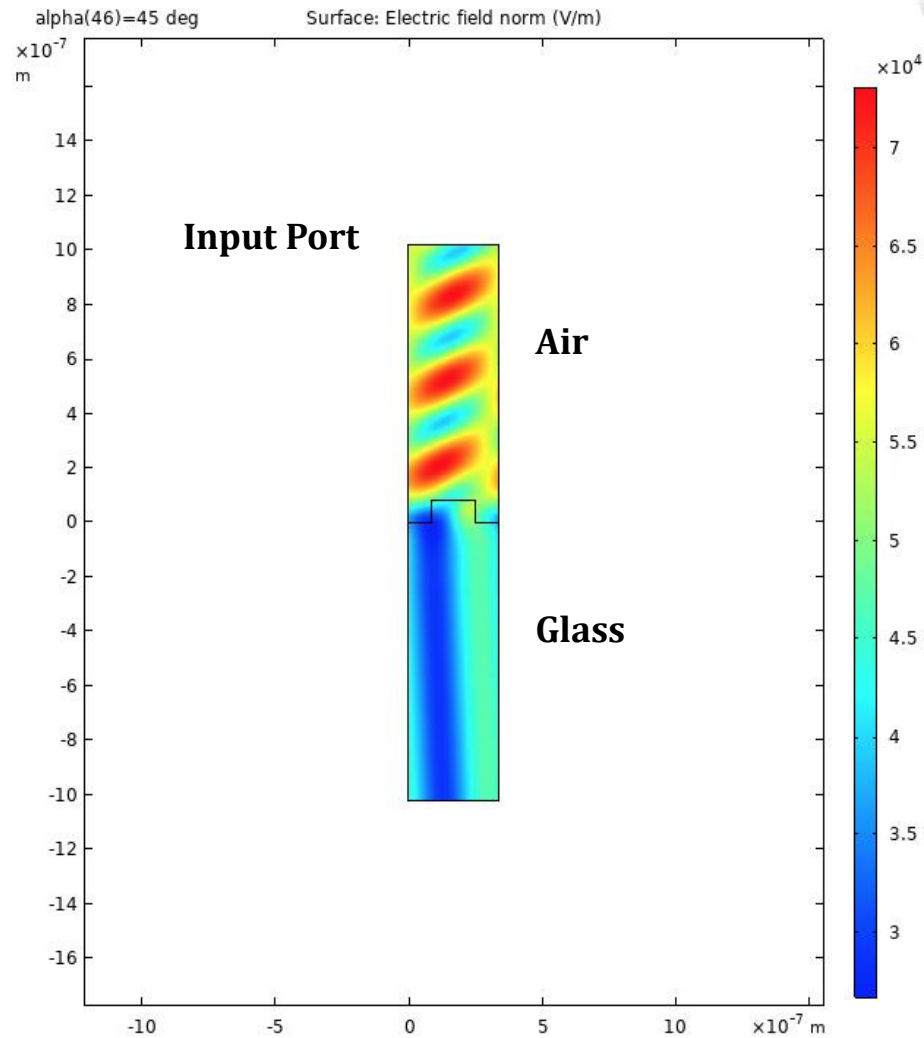


Figure 14. Total field for diffraction grating without PML. The range of the magnitude associated with this case varies significantly from the case with PML present. The angle of incidence is 45 degrees.

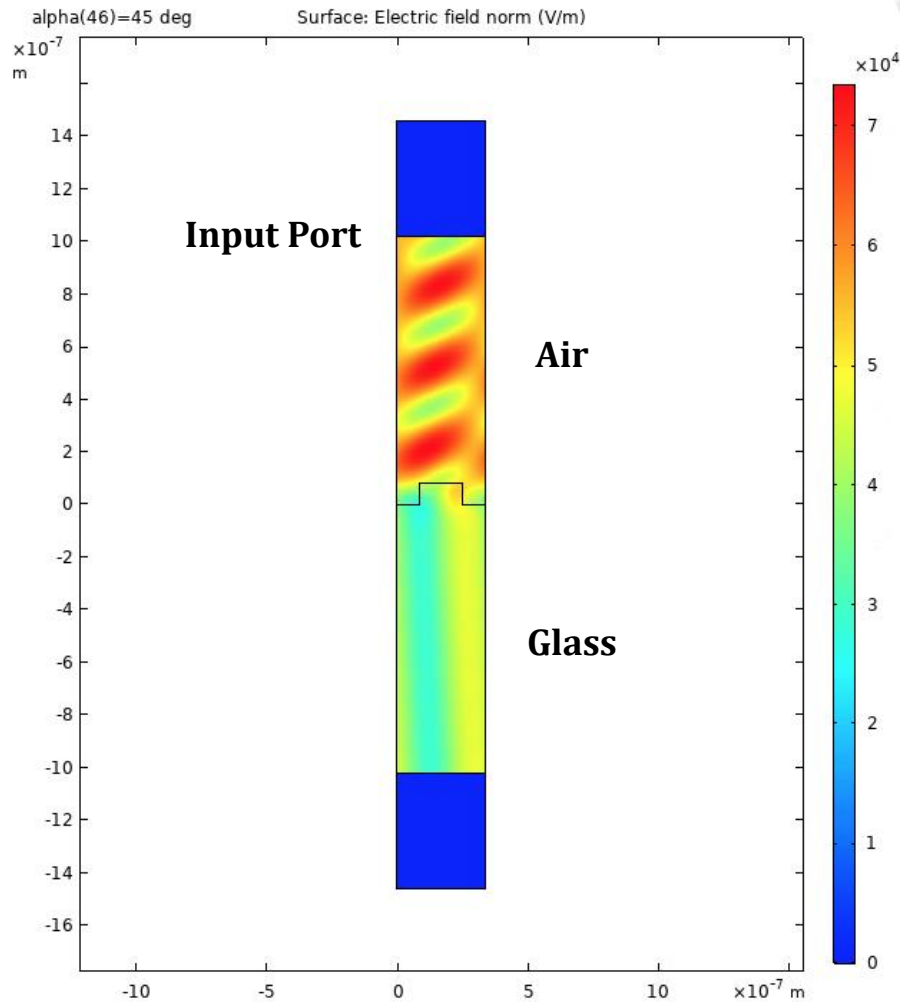


Figure 15. Total field for diffraction grating without PML. The range of the magnitude associated with this case varies significantly from the case with PML present. The angle of incidence is 45 degrees.

After verifying that all boundary and port conditions used for the binary grating shown in Figure 13 were correct, the author simulated the grating using the wavelength and grating period optimized for DPM on-chip (see Fig. 16). Because COMSOL does not have a variable that automatically computes the diffraction efficiencies, the author computed the sum of reflectance and transmittance for each diffraction order. For the binary grating in Fig. 16, only the 0th, +1, and -1 orders were non-zero. The 0th order had a sum of 0.49 for the transmittance and reflectance. The +1 and -1 orders both had a sum of 0.254. Because the sum of the transmittance and reflectance for all three orders equaled one to within rounding errors and light was evenly divided between the +1 and -1 orders, the author believes that this simulation was accurate.

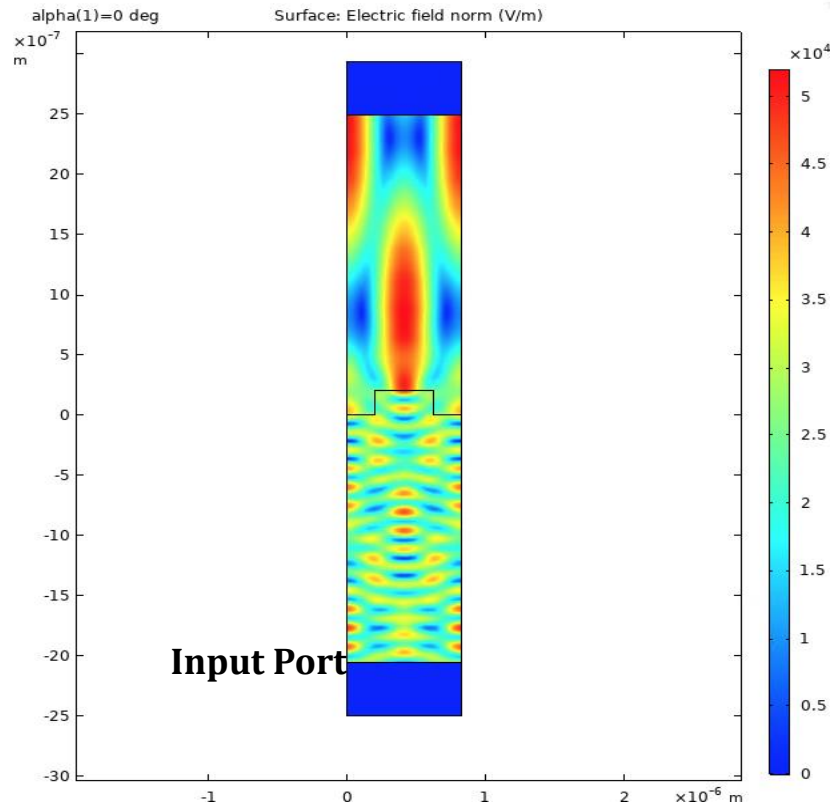


Figure 16. Total field for normal incident light on binary grating with glass (bottom)/air (top) regions. Power of incident field set to 1 W. Grating constant $\Lambda = 833$ nm and length $\lambda = 405$ nm. PMLs have width 1λ .

A Poynting vector analysis was conducted on the simulation to verify that no reflections occurred at the edge of the region of interest (see Fig. 17). Figure 18 of the air-grating interface demonstrates that the majority of the light is being transmitted through the grating.

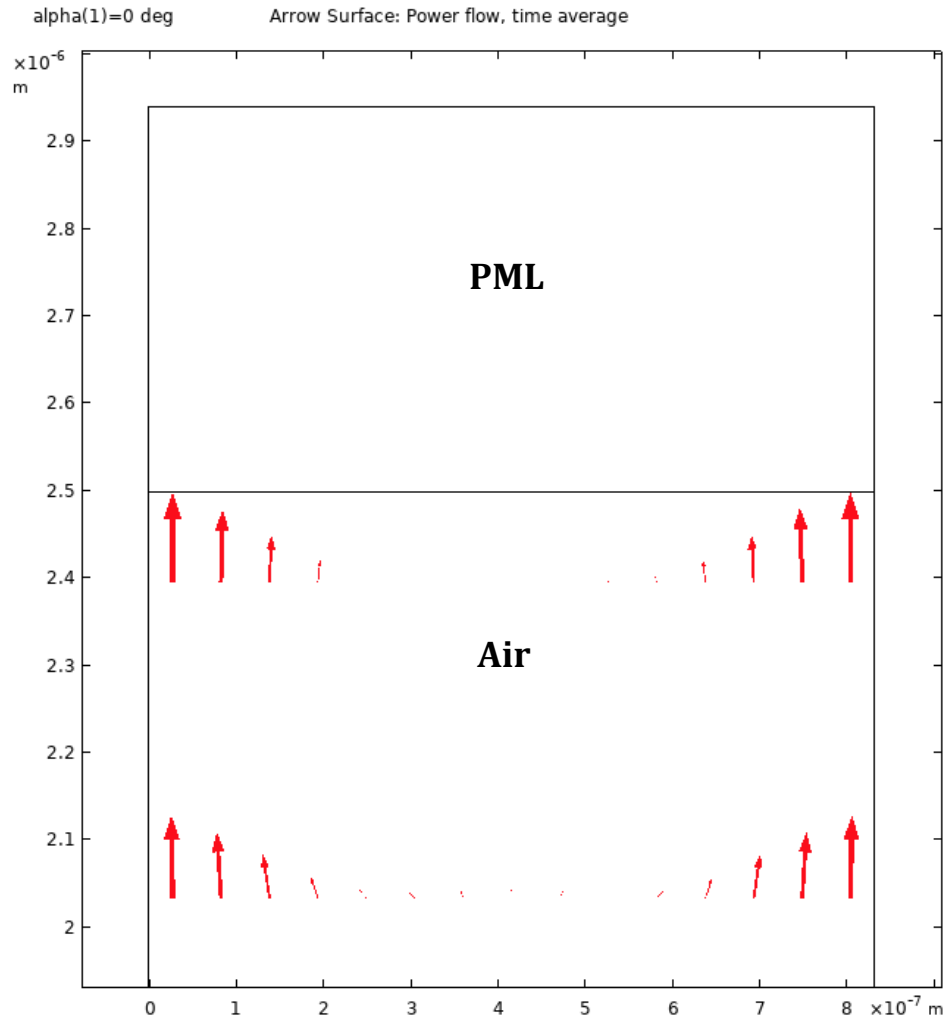


Figure 17. Poynting Vector at PML/air interface. PML thickness is 1λ . No reflections are visible at the PML/air interface.

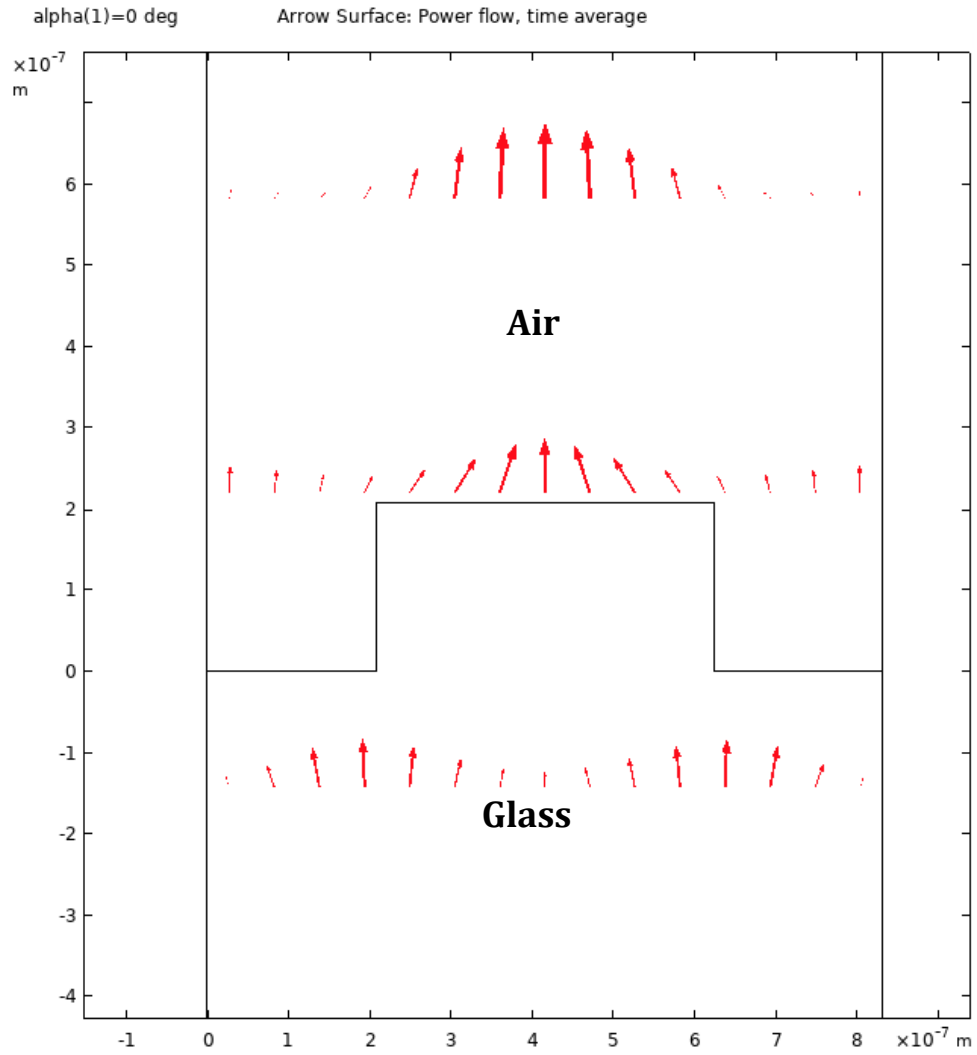


Figure 18. Poynting Vector at air-glass interface. PML thickness is 1λ . The magnitude of the vectors at the air-glass interface show that the majority of the light is transmitted through the glass.

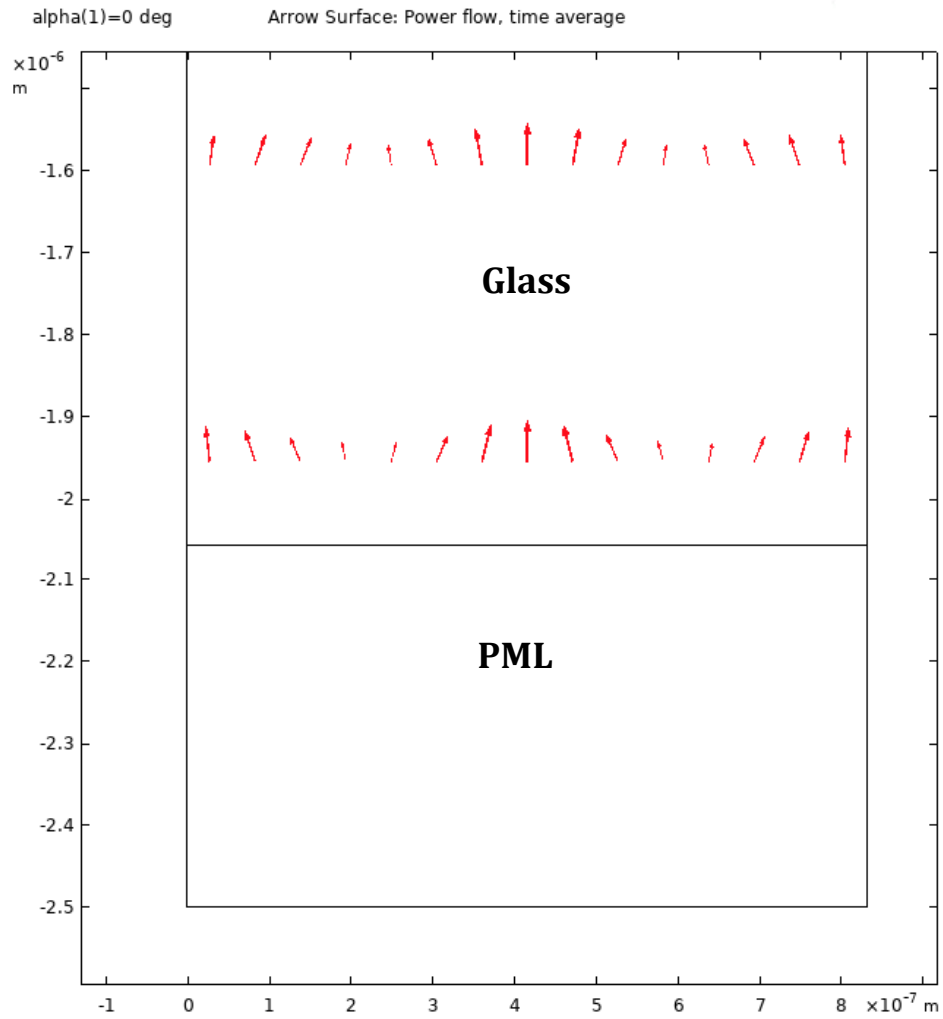


Figure 19. Poynting Vector at glass/PML interface. PML thickness is 1λ . No reflections are present along the edge of the simulation region.

5.4 Blazed Diffraction Grating Simulation

After verifying that the simulations for the binary grating were correct, the author simulated the total field and associated Poynting vector for a blazed grating (see Fig. 20). The blaze angle was varied and the resulting transmittance for each blaze angle was observed (see Table 3). The simulation confirms that the blazed geometry increases transmittance for the +1 order.

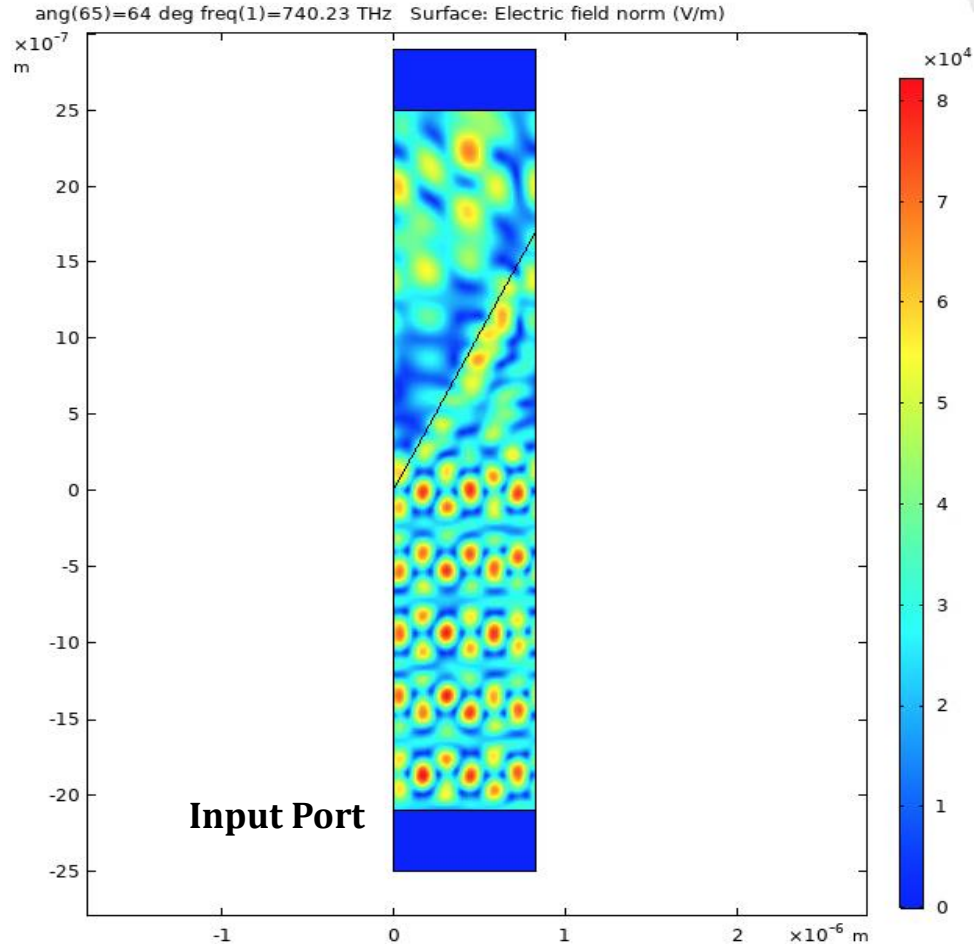


Figure 20. Total field for blazed grating. Incident angle is zero degrees. Power of incident field set to 1 W. Perfectly matched layers have same width as grating constant $\Lambda = 833$ nm and thickness $\lambda = 405$ nm. Pictured above is the electric field profile for $\Theta_B = 64^\circ$. Transmittance for the +1 order is 0.789.

The following table shows simulated transmittance for several blazed gratings (i.e., varied blaze angles). Transmission for the +1 order is highest for $\Theta_B=64^\circ$; nonetheless, the results are promising because the simulated transmittance associated with $\Theta_B=37^\circ$ is similar to the measured value for a Thorlabs grating having the same blaze angle (see Fig. 21). This simulation may be improved by ensuring that the grating length is an integer multiple of 2π so that destructive interference does not occur.

Table 3. Blaze Angle versus Transmittance for +1 order. When light has normal incidence, the highest transmission occurs when $\Theta_B=64^\circ$. Transmission for the 37° blaze angle is highlighted because this is the angle that Thorlabs uses for its manufactured gratings. The simulated transmittance is 42.6% and is similar to the measured value from Thorlabs (i.e., 38%).

Blaze Angle (deg)	Transmittance, Order +1	Thorlabs ~ 38%
34	0.585	
36	0.556	
37	0.426	
38	0.294	
39	0.721	
60	0.647	
61	0.726	
62	0.718	
63	0.766	
64	0.789	
65	0.716	

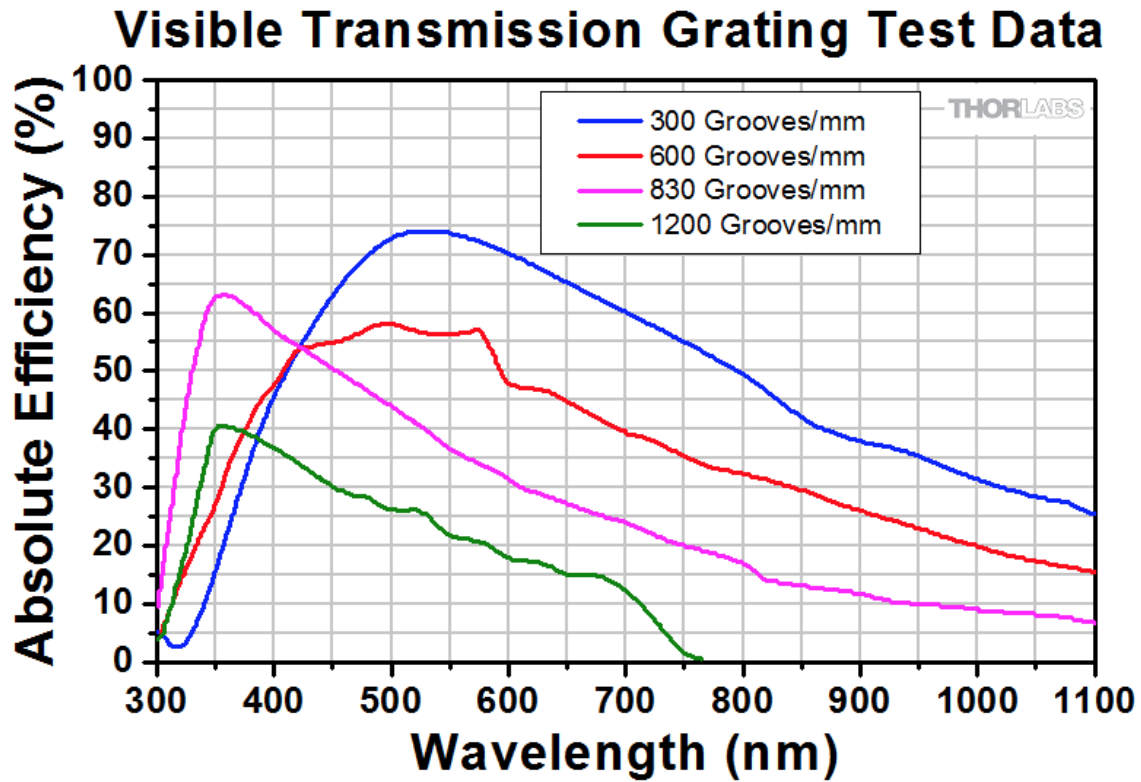


Figure 21. Thorlabs Blazed Grating Specifications. For 405-nanometer light interacting with a grating having 1200 lines/mm (which is needed for DPM on-chip Design #1), the diffraction efficiency is approximately 38%. This value supports simulated results [15].

6. Lens Design

Lens 1 and lens 2 can be fabricated as classical optics or as diffractive optical elements (DOEs). The author proposes utilizing the latter to save space. Fabricating lens 2 as a Fresnel lens is also useful because it would be extremely thin as a conventional biconvex lens (the associated sag is 0.6 mm).

The Fresnel lens has been used for numerous applications due to its ability to function as a condenser, beam collimator, and imaging lens. Fresnel lenses are often found in lighthouses, traffic signals, and detection systems [16]. They have also been utilized to focus x-rays, form microscope systems, and enhance lab-on-chip devices [17, 18]. In the case of the lab-on-chip device, a Fresnel lens focused light onto a microfluidic channel to increase the sensitivity of a fluorescence detection system for *e. coli* bacteria. Using $\lambda = 365 \text{ nm}$, authors in [18] could detect bacteria in a saline solution with a ratio of 1:10,000,000.

After a brief discussion on the classical biconvex lens, the author will present a modified Fresnel lens that maintains the same focusing properties of the classical device but uses less material than both a classical lens and a standard Fresnel lens.

6.1 Classical Biconvex Lens 1

To fabricate a biconvex lens with the focal length and numerical aperture of lens 1 (Table 1), one would need to determine the lens diameter, D , and radius of curvature, R_1 . Equation 23 shows the lens diameter calculation:

$$\begin{aligned}
D &= 2f_1NA_1 \\
&= 2(2.5 \times 10^{-3})(0.648) \\
&= 3.24 \text{ mm}
\end{aligned} \tag{23}$$

The radius of curvature is determined from the lens equation (Equation 24):

$$\frac{1}{f} = (n_{lens} - 1) \left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n_{lens}-1)d}{n_{lens}R_1R_2} \right], \tag{24}$$

where n_{lens} is the refractive index of the lens and $R_2 = -R_1$. Assuming that the lens is thin, $d \rightarrow 0$ and we arrive at the thin lens equation:

$$\frac{1}{f} = (n_{lens} - 1) \left[\frac{1}{R_1} - \frac{1}{R_2} \right] \tag{25}$$

From $f_1 = 2.5 \text{ mm}$ and $n_{lens} = 1.5229$ for glass, Equation 25 becomes

$$\begin{aligned}
\frac{1}{2.5 \times 10^{-3}} &= (1.5229 - 1) \left[\frac{2}{R_1} \right] \\
\Rightarrow R_1 &= 2.61 \text{ mm}
\end{aligned} \tag{26}$$

Knowing the lens diameter and radius of curvature, one can calculate the sag of the lens, which provides insight into the thickest region of a lens. A physical representation of sag is shown in Fig. 22, and its equation follows (Equation 27).

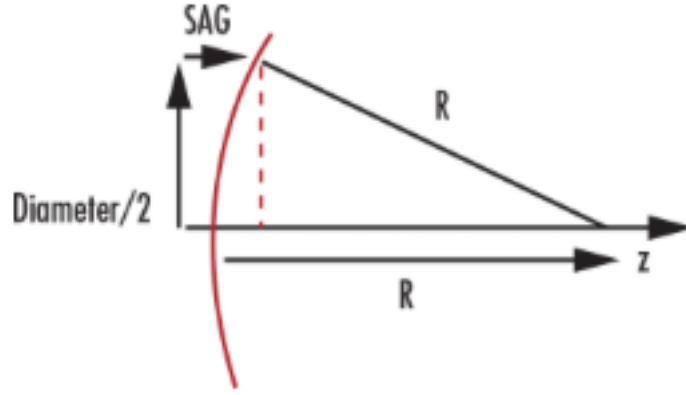


Figure 22. Visual representation of lens sag. Radius of curvature and lens diameter are required to calculate lens sag [19].

$$sag = R - \sqrt{R^2 - \left(\frac{D}{2}\right)^2}, \quad (27)$$

The sag for the optimized lens equals 0.562 mm, resulting in a center thickness of 1.125 mm for a traditional lens. With a Fresnel lens maintaining the same focal length and numerical aperture, one can scale the sag of the lens to microns or nanometers (see Fig. 23) [20].

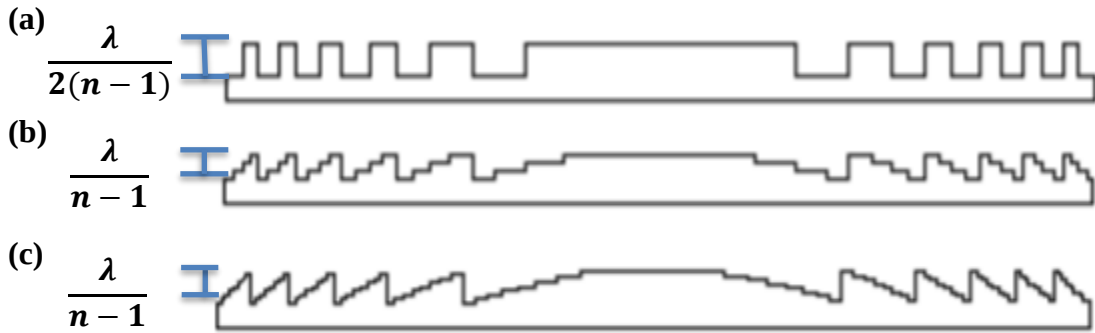


Figure 23. Fresnel phase plate and Fresnel lenses. (a) A Fresnel phase plate with height equal to $\lambda/2$. (b) – (c) Fresnel lenses with height equal to λ . Variation exists in the amount of steps used to fabricate each zone region in (b) and (c). The latter more closely approximates kinoform lens [14].

6.2 Fresnel Lens

The surface profile is divided into sections along the lens diameter; these sections are then shifted until they are located in the same plane. The result is a lens with significantly reduced volume/weight that has near-diffraction-limited performance (see Fig. 24) [14, 21].

A Fresnel lens is a specialized case of a Fresnel phase plate. Both are composed of Fresnel zones, which are alternating regions that naturally occur in small circular apertures. Note that in circular apertures, however, these zones are invisible. To visualize Fresnel zones, consider concentric circles composed of radii that ensure that each zone contains the same area. The radius of each successive zone increases the optical path length to a point P, located on the optical axis at a distance r_0 from the aperture center, by a half-wavelength (i.e., π). Whereas consecutive zones (i.e., 1 and 2) cause destructive interference of light, alternating zones (i.e., 1 and 3) contribute to constructive interference. As a result, Fresnel zone plates were created to block zones that destructively interfere with each other in order to increase light intensity. Although all zones contain the same area, higher zones have less impact on the resulting intensity. This is related to the fact that when an aperture is opened wide enough, it is as though an electric field is traveling without any obstruction.

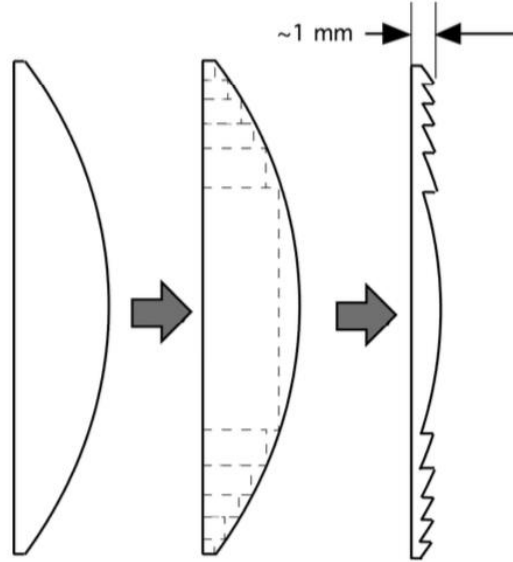


Figure 24. Relation between plano-convex lens and Fresnel lens. This image shows how parts of a plano-convex lens that do not contribute to beam curvature are removed in a Fresnel lens [14].

An alternative to blocking zones that cause destructive interference is to instead induce a π -phase shift so that previously blocked light can constructively interfere with zones already unobstructed. This further increases intensity. This solution exists and is known as a Fresnel phase plate. One can think of a phase plate as a binary grating with spatially varying periods. Similarly, light diffracts into the +1 order for a phase plate with approximately 41% efficiency, theoretically [14, 17]. Fabricated structures demonstrated 30-35% efficiency [20]. The +1 order light focuses on the optical axis. The height of each zone is $\frac{\lambda}{2(n-1)}$ (i.e., phase shift of π), as shown in the cross section of the phase plate in Fig. 25. Each zone is commonly referred to as a π phase region due to the associated optical path distance.

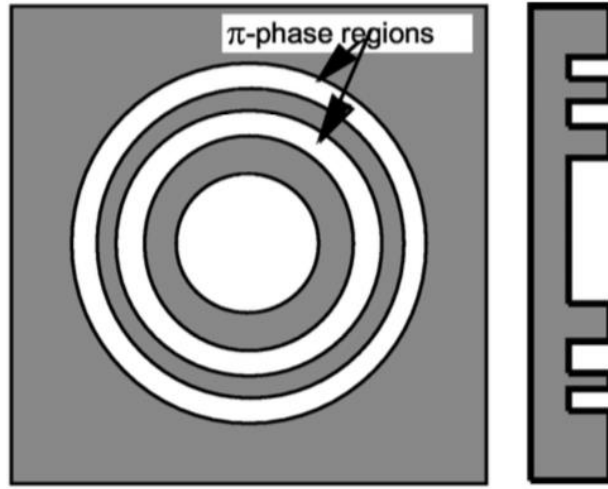


Figure 25. Fresnel Phase Plate. A top view and cross section of a phase plate [14].

Similar to a phase plate, a Fresnel lens also has spatially varying periods due to variation in zone widths; however, the zone transitions of a Fresnel lens occur when the optical path difference increases by one wavelength (i.e., phase shift of 2π) instead of by a half-wavelength. Ideally, a Fresnel lens approximates the surface profile of a classical plano-convex lens, resulting in what appears to be a blazed grating with spatially varying periodicity. The sag of a Fresnel lens does not follow the equation for a classical lens (Equation 27). Instead, its thickness is $\frac{\lambda}{n-1}$ (i.e., 2π).

The blazed profile increases the diffraction efficiency for +1 order light from 41% to 99%, theoretically [14, 22, 17]. Because blazed gratings and, thus, kinoform lenses are difficult to fabricate with conventional photolithography, binary steps are often used to approximate the curved structures. The more steps used, the better the approximation. Typically, 16 steps are chosen because they are feasible to fabricate, and this amount maintains high diffraction efficiency. From [14], one can determine how the number of steps in each zone affects the diffraction efficiency in the +1 order:

$$\eta_{+1} = \left[\frac{\sin(\frac{\pi}{N})}{\frac{\pi}{N}} \right]^2, \quad (28)$$

where N is the number of steps in a zone. The diffraction efficiency of a fabricated structure will be less than the theoretical value when deviation in any of the following parameters occurs: lens height, zone width, swelling of surface profile (i.e., from planar steps to curved), and sidewall tilt at zone transitions. Fresnel lenses with 60-80% efficiency have been fabricated [22, 23].

6.2.1 Fresnel Height Determination

With Fresnel phase plates, alternating zones introduce a π phase shift to incident light. For a Fresnel lens, alternating zones introduce a 2π phase shift. The step height of these elements determines the value of the shift. Derivation of the step height for a Fresnel lens follows.

The transmission function of a glass plate with thickness, d , is

$$t = e^{-jnk_0d}, \quad (29)$$

where $k_0 = 2\pi/\lambda_0$. Therefore, the phase difference introduced to light that interacts with a glass slab and an air region of the same thickness (see Fig. 26) is

$$\Delta\phi = \frac{2\pi n_{glass}d}{\lambda} - \frac{2\pi n_{air}d}{\lambda} = \frac{2\pi d(n_{glass} - 1)}{\lambda}, \quad (30)$$

because $n_{air} = 1$. In order to create a 2π phase shift between the two regions, one can set $\Delta\phi = 2\pi$ and solve Equation 30 for d :

$$d_{2\pi} = \frac{\Delta\phi\lambda}{2\pi(n_{glass} - 1)} = \frac{\lambda}{n_{glass} - 1}. \quad (31)$$

For a π phase shift between the two regions, $\Delta\phi = \pi$ and $d_{\pi} = \frac{\lambda}{2(n_{glass}-1)}$.

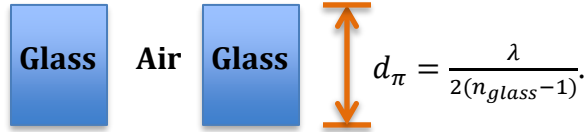


Figure 26. Glass slab used in height derivation. A visual representation showing how height of glass slabs separated by air affects the phase delay induced by the slabs. For a π phase delay, a height of $\frac{\lambda}{2(n_{glass}-1)}$ is required.

6.2.2 Fresnel Lens: A Specialized Phase Plate

A simple case consisting of a Fresnel lens with four steps per zone can be used to demonstrate why a lens with 2π phase regions and height $d = \frac{\lambda}{n_{glass}-1}$ is a specialized version of a phase plate with π phase regions and height $d = \frac{\lambda}{2(n_{glass}-1)}$. Noting Fig. 27, one can see that the step height difference between consecutive steps is $d_{step} = \frac{\lambda}{4(n_{glass}-1)}$.

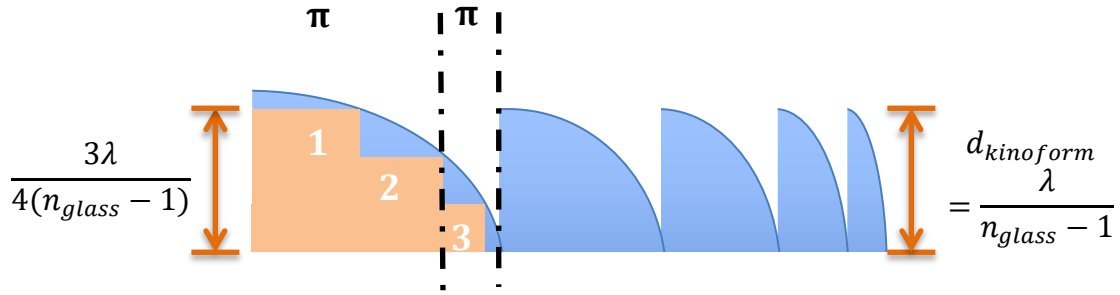


Figure 27. Phase region comparison. The normal 2π phase regions of a Fresnel lens can be divided into π sub-regions. Doing so helps one see why the lens is a specialized case of a phase plate. Steps are numbered in white. The fourth step (unlabeled) has step height of zero.

As a result, the total height for a 2π zone divided into four regions is $d_{total\ height} = \frac{3\lambda}{4(n_{glass}-1)}$. If we assign step 1 as the tallest subdivision and step 4 as the base with zero height, we can determine the phase shifts associated with alternating steps (see Fig. 28).

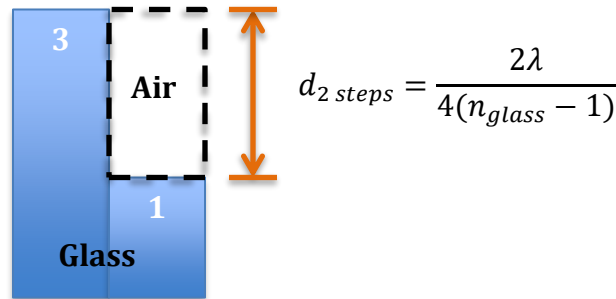


Figure 28. Height difference between alternating steps 1 and 3. The height can be used to show that the phase delay between the two steps is π , just as the case for a Fresnel phase plate.

Although all four steps compose a single 2π zone, one can group step 1 and step 2 into a single π zone and do the same for step 3 and step 4. Alternating steps, which occupy

different π phase regions, exhibit a π phase shift with respect to each other, which is analogous to the Fresnel phase plate case:

$$\begin{aligned}
 \Delta\phi_{\text{alternate steps}} &= \frac{2\pi n_{\text{glass}} d}{\lambda} - \frac{2\pi n_{\text{air}} d}{\lambda} & (32) \\
 &= \frac{2\pi n_{\text{glass}}}{\lambda} \left(\frac{2\lambda}{4(n_{\text{glass}} - 1)} \right) - \frac{2\pi n_{\text{air}}}{\lambda} \left(\frac{2\lambda}{4(n_{\text{glass}} - 1)} \right) \\
 &= \frac{\pi n_{\text{glass}}}{(n_{\text{glass}} - 1)} - \frac{\pi}{(n_{\text{glass}} - 1)} = \frac{\pi(n_{\text{glass}} - 1)}{(n_{\text{glass}} - 1)} = \pi
 \end{aligned}$$

Note that the value of d for this comparison should be constant, so the height of the air region was written in terms of variables that describe a glass step.

6.2.3 Zone Derivation

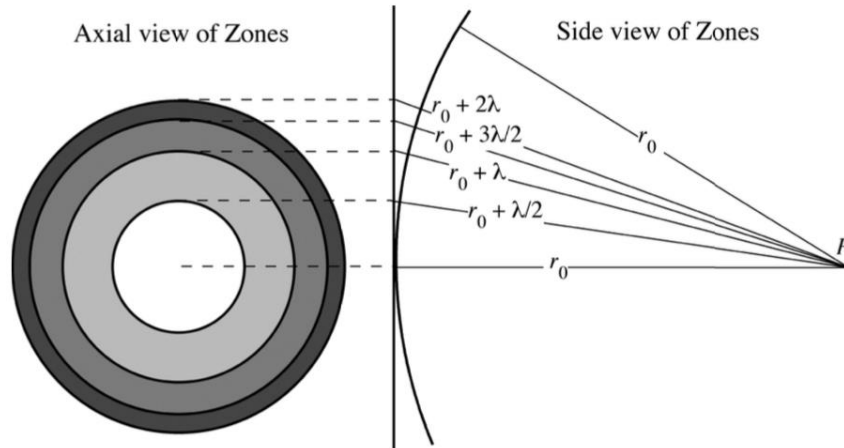


Figure 29. Optical path difference between zones. Top view and side view of Fresnel lens what shows how each zone increases the optical path difference by $\lambda/2$ for a phase plate. For a Fresnel lens, this distance is λ [14].

Using simple geometry, as shown in Fig. 29, one can derive the radii of the 2π phase regions:

$$\begin{aligned}
 (f + m\lambda)^2 &= f^2 + r_m^2 & (33) \\
 \Rightarrow r_m^2 &= (f + m\lambda)^2 - f^2 \\
 &= f^2 + 2mf\lambda + (m\lambda)^2 - f^2 \\
 &= (m\lambda)^2 + 2mf\lambda
 \end{aligned}$$

Assuming $\lambda \ll f$:

$$\begin{aligned}
 r_m^2 &= 2mf\lambda \\
 \Rightarrow r_m &= \sqrt{2mf\lambda},
 \end{aligned}$$

where m is a positive integer. Once again, let us examine the case where we divide a 2π phase region into four sub-regions. As a result, the modified zone radii, r'_m , in the new coordinate system will change as follows:

$$\begin{aligned}
 f^2 + r'^2_m &= \left(f + \frac{\lambda m}{4}\right)^2 & (34) \\
 f^2 + r'^2_m &= f^2 + \frac{f\lambda m}{2} + \left(\frac{\lambda m}{4}\right)^2
 \end{aligned}$$

Assuming that $\lambda \ll f$,

$$\begin{aligned}
 \Rightarrow r'^2_m &= \frac{f\lambda m}{2} \\
 r'_m &= \sqrt{\frac{f\lambda m}{2}}.
 \end{aligned}$$

One can verify that this modified radius equation is correct by comparing r_1 to r'_4 because they are equivalent points. Both r_1 and r'_4 equal $\sqrt{2f\lambda}$. One can also verify equation correctness by determining whether zones have the same area. If we compare the areas of subdivisions one and two, we see that this is true:

$$\begin{aligned}
 A_{zone2} &= A_{circle2} - A_{circle1} \\
 &= \pi(r'_2)^2 - \pi(r'_1)^2 \\
 &= \pi(f\lambda) - \pi\left(\frac{f\lambda}{2}\right) \\
 &= \frac{\pi f\lambda}{2}
 \end{aligned} \tag{35}$$

Because $A_{zone1} = \frac{\pi f\lambda}{2}$, we see that zones 1 and 2 have the same area (see Fig. 30).

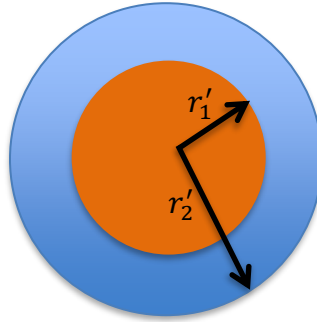


Figure 30. Concentric circles of modified radii, r'_1 and r'_2 . One can compute the area of the two circles and verify that they are equal, which is required of Fresnel zones.

Lastly, a generalized equation for the modified radii composing zones with N subdivisions for the lens in Fig. 31 is:

$$\begin{aligned}
 f^2 + r_m'^2 &= \left(f + \frac{\lambda m}{N}\right)^2 \\
 f^2 + r_m'^2 &= f^2 + 2f\left(\frac{\lambda m}{N}\right) + \left(\frac{\lambda m}{N}\right)^2
 \end{aligned} \tag{36}$$

Assuming that $\lambda \ll f$,

$$\Rightarrow r_m'^2 = \frac{2f\lambda m}{N}$$

$$r_m' = \sqrt{\frac{f2\lambda m}{N}}.$$

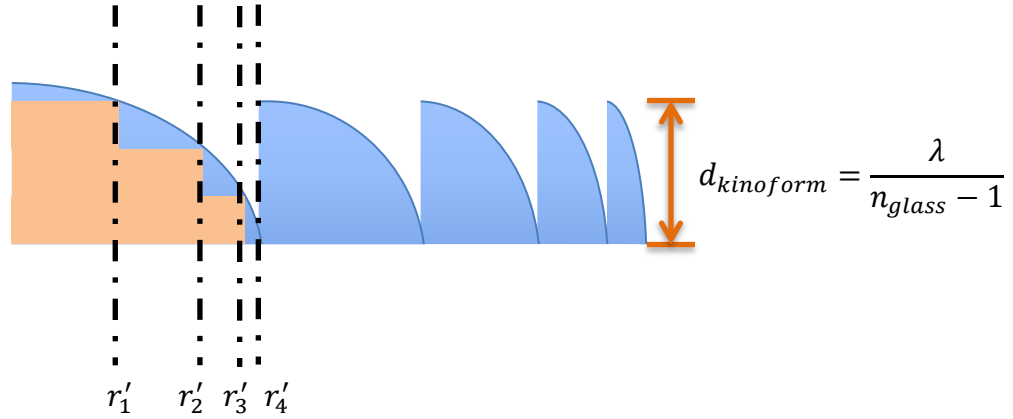


Figure 31. Cross section of Fresnel lens that shows modified radii due to subdivisions of zone. Note that $r'_4 = r_1$ where r_1 is the original radius of the first zone without subdivisions.

6.2.4 Initial Fresnel Lens Fabrication Strategy

Photolithography and etching are conventionally used to fabricate Fresnel lenses. Photolithography is an iterative process that involves spin-coating photoresist on top of a substrate and utilizing a physical mask to expose specific regions to UV light. Light exposure causes a chemical reaction within the photoresist. Depending on the type used, exposed regions either dissolve or remain after development. Finally, the substrate is etched to achieve the desired lens profile (see Fig. 32). To obtain profiles with more than two levels using photolithography, one must use multiple masks, which increases cost.

Instead, grayscale direct-write lithography or grayscale electron beam (e-beam) lithography can be used to fabricate continuously varying structures without physical masks [20, 24-26].

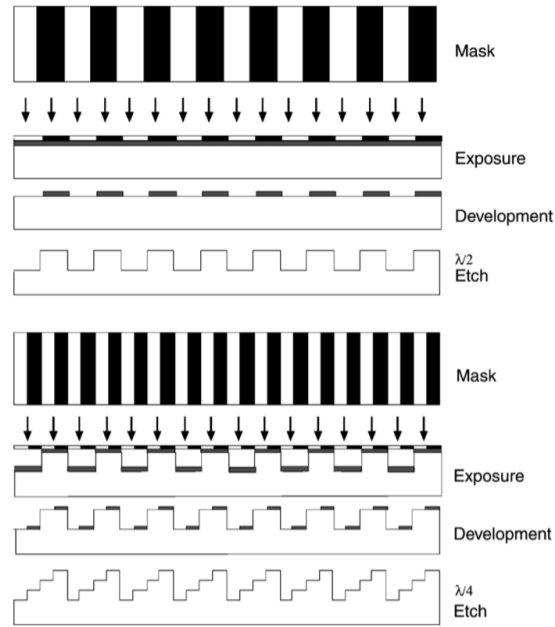


Figure 32. Fresnel lens fabrication. Photolithography and dry etching are used to fabricate the lens. When four subdivisions per region are used to approximate the zone profile, two physical masks and two separate etches are required. The first etch provides a trench equal to a half-wavelength. The second etch results in a step height of one-quarter wavelength [14].

Direct laser-write lithography is a good option when fabricating Fresnel lenses with larger dimensions. Like e-beam lithography, it is mask-less; however, a laser is used as the source. It scans through a spatial light modulator that undergoes optical density changes. As a result, a single mask can be used to fabricate varying heights after one exposure.

E-beam lithography tends to be a slower process than optical lithography, but it has higher resolution. Fabrication on the scale of nanometers is possible with e-beam

lithography as opposed to the micron-scale fabrication associated with optical lithography. Like photolithography, e-beam lithography also uses photoresist; however, it is sensitive to electron beams rather than light. An electron beam modulates photoresist exposure dose, creating varying photoresist thickness across a sample. Silicon and glass are common substrate material for Fresnel lenses fabricated with e-beam lithography. The standard photoresist used is polymethyl methacrylate (PMMA), a positive tone resist that removes exposed regions after development. The dose of an e-beam system, or the quantity of charge per unit area, is an important parameter than one adjusts to achieve a desired grayscale profile. Contrast curves are created for particular samples in order to determine the relation between applied exposure dose and photoresist height. A sharper height resolution is associated with steeper contrast curves.

Regardless of which type of lithography is used to pattern the photoresist, reactive ion etching (RIE) may be used to transfer the pattern into the substrate. See Fig. 33. Deep reactive ion etching (DRIE) is utilized when a height is large and a fast etch rate is required [27].

In order to attain a desired profile, one must: 1) Select photoresist type and initial thickness, noting that for diffractive elements, resist thickness must be significantly larger than the depth of the final structure. These thick photoresists may cause non-uniform thickness across the sample, thus impacting dose curves. 2) Determine the dose-depth curve by exposing a large area with different doses. 3) Characterize etch selectivity, i.e., determine how substrate etch rate differs from the photoresist etch rate by creating various pattern sizes and densities. Note that oxygen plasma can sometimes be added to adjust selectivity. 4) Optimize selectivity of RIE by selecting the appropriate pressure, power, and

gas ratio. 5) Determine the appropriate ratio of isopropyl alcohol (IPA) to methyl isobutyl ketone composing the developer.

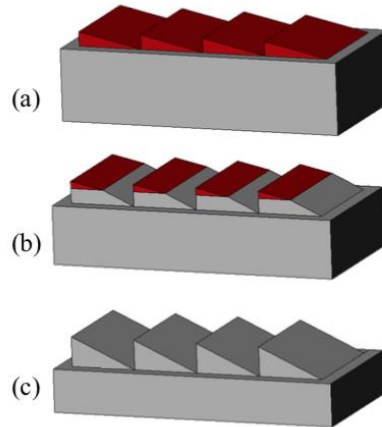


Figure 33. Grayscale lithography combined with RIE for blazed grating profile. Research shows that etch selectivity strongly influences successful fabrication of the sawtooth profile. Authors in [27] used a 2:1 selectivity of silicon to photoresist to achieve their result [27].

A script can be used to create the mask for Fresnel lens simulations and e-beam fabrication. Lens simulations have been shown to predict the effectiveness of a Fresnel lenses [17]. For the e-beam system, alignment marks should be added to assist with alignment of structures.

6.2.5 Lens Fabrication Limitations

A limitation of e-beam lithography includes the proximity effect, which occurs when the dose covers an area larger than the beam diameter. When electrons collide with atoms in the photoresist and substrate, the beam can sometimes spread. One can reduce this effect by increasing beam energy. A reduction in beam dispersion occurs with energy increase

because fewer electrons interact with atoms in the substrate as a result. To ensure that writing time is not significantly increased, one must increase the dose current.

Choosing to fabricate lens 1 as a Fresnel lens introduces a new limitation: it affects the pinhole spacing outlined in the Design Constraints section. Conventionally, the incident angle of a plane wave approaching a Fresnel lens is 0° . Because the incident light is coming from a diffraction grating for the DPM on-chip design, the +1 order beam will approach the Fresnel lens at an angle $\theta_{i,lens} = \theta_{+1,grating}$. As a result, the author proposes that the +1 order of the Fresnel lens, $\theta_{+1,lens}$, which focuses parallel to the optical axis, will have a new diffraction angle, $\theta'_{+1,lens}$. When the incident angle is zero, all +1 order light focuses in the same plane as shown in Fig. 34; however, if the incident angle changes, the focal point will shift along the y-axis as shown in Figs. 35 and 36. A shift in the position where the +1 order beam focuses will directly affect the position of the pinhole, which filters this beam.

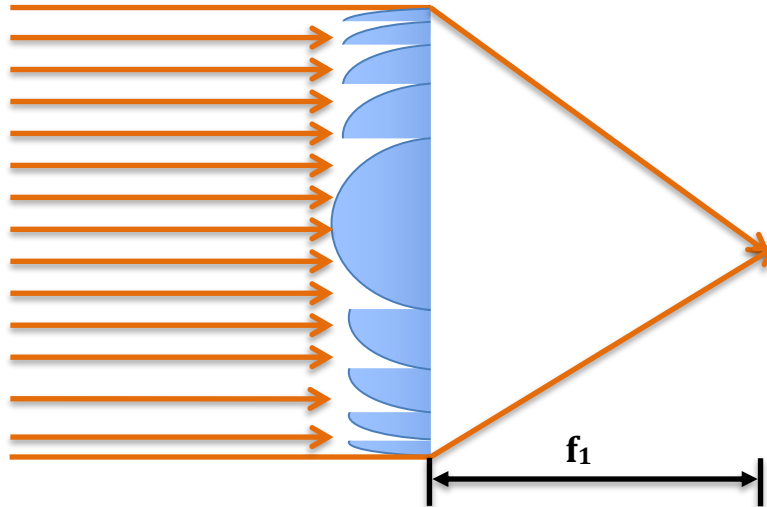


Figure 34. Focusing of plane wave illumination by Fresnel lens. When light comes in normal to the lens, it will focus to a point where all +1 orders from the lens meet.

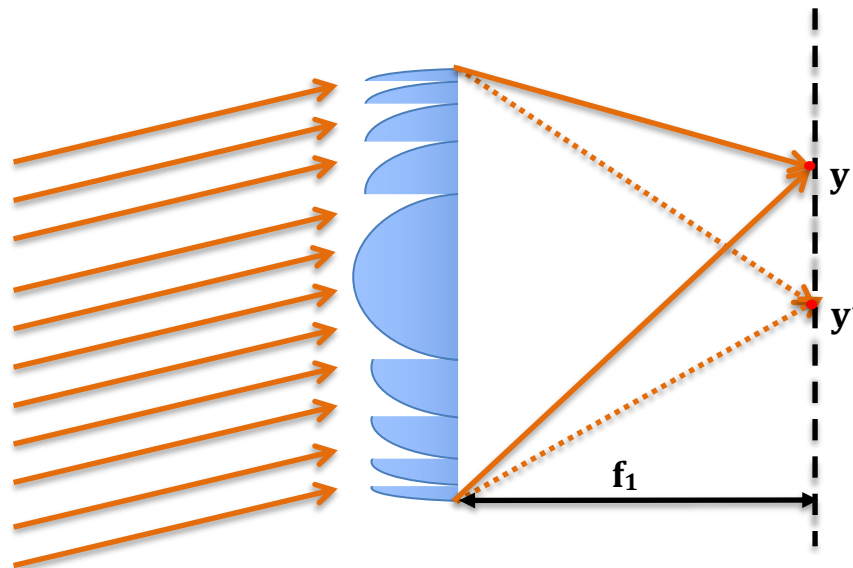


Figure 35. Focusing of plane wave illumination by Fresnel lens. Author proposes that when light comes in at an angle to the lens, the focal point will shift.

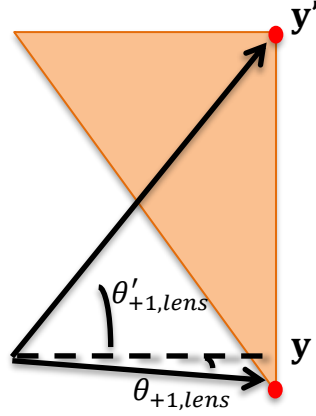


Figure 36. Geometry of shift. Using the tangent function, one can determine how the focal point shifts with respect to the focal point associated with normal incidence.

One should first determine the diffraction angle of the +1 order beam that leaves the grating, $\theta_{+1,grating}$, using Equation 37.

$$\Lambda[\sin \theta_m - \sin \theta_i] = m\lambda \quad (37)$$

$$\Rightarrow \sin \theta_{+1,grating} = \frac{\lambda}{\Lambda_{grating}}$$

$$\Rightarrow \theta_{+1,grating} = \sin^{-1}\left(\frac{\lambda}{\Lambda_{grating}}\right) = 0.191254 \text{ radians} \approx 10.96^\circ.$$

This becomes the incident angle for the Fresnel lens. Because a Fresnel lens also obeys Equation 37, one can determine the new diffraction angle, $\theta'_{+1,lens}$, that results when the incident angle is nonzero.

$$\sin \theta'_{+1,lens} - \sin(0.191254) = \frac{\lambda}{\Lambda_{lens}} \quad (38)$$

$$\Rightarrow \theta_{+1,lens} = \sin^{-1}\left(\left(\frac{\lambda}{21.96 * 10^{-6}}\right) + \sin(0.191254)\right) = 0.2207 \approx 12.65^\circ$$

where $\Lambda_{lens} = \left[r_2 + \frac{r_3 - r_2}{2} \right] - \left[r_1 + \frac{r_2 - r_1}{2} \right]$.

Note that if the +1 order beam had normal incidence, the diffraction angle would be:

$$\theta_{+1,lens} = \sin^{-1} \left(\frac{\lambda}{\Lambda_{lens}} \right) = 0.02883 \text{ radians} = 1.652^\circ$$

A Fresnel lens has spatially varying grating periods that are determined by the zone widths. Therefore Λ_{lens} should be a function of position rather than a constant. For simplicity, we will assume a constant grating period set to a value from a localized region of the lens to demonstrate how the focal point of the lens will shift when the incident angle is non-zero.

Using Fig. 37 and the assumption that light will focus in the same focal plane but will be shifted in y, one can determine the y-shift:

$$\begin{aligned} \tan \theta_{+1,lens} &= \frac{y}{f_1} \text{ and } \tan \theta'_{+1,lens} = \frac{y'}{f_1} \\ \Rightarrow |y| &= 0.086514 \text{ mm and } y' = 0.673064 \text{ mm} \end{aligned} \tag{39}$$

As a result, the author predicts that the pinhole will shift by 0.587 mm.

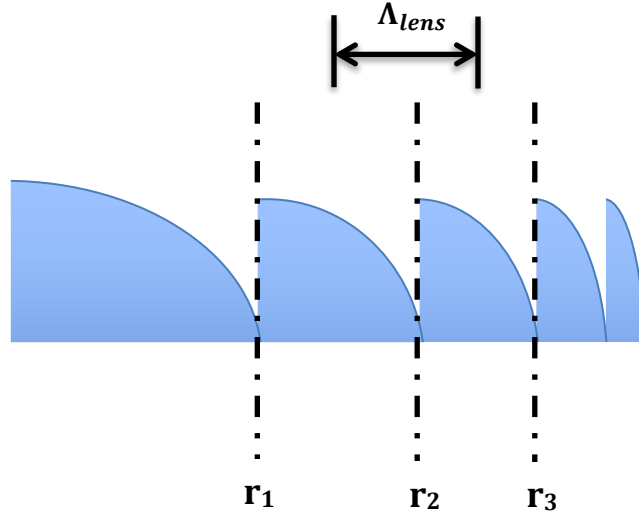


Figure 37. Local region on Fresnel lens. The grating period for the region above was used in Equation 38.

The author found a prior application in the literature that supports the idea of a pinhole shift [28]. A solar concentrator composed of a grating and a Fresnel lens was used to spectrally separate light and then focus it onto a solar cell (see Fig. 38). Both 0th and +1 order beams from the grating were used. The Fresnel lens contained a uniform grating period. As a result, focused light was shifted in the x- and y-directions (i.e., the light focused in a new plane and was shifted vertically). Céline Michel et. al proposed using a Fresnel lens with spatially varying periods in order to focus light in the same plane as the 0th order, which supports the assumption made for Equation 39 (see Fig. 39).

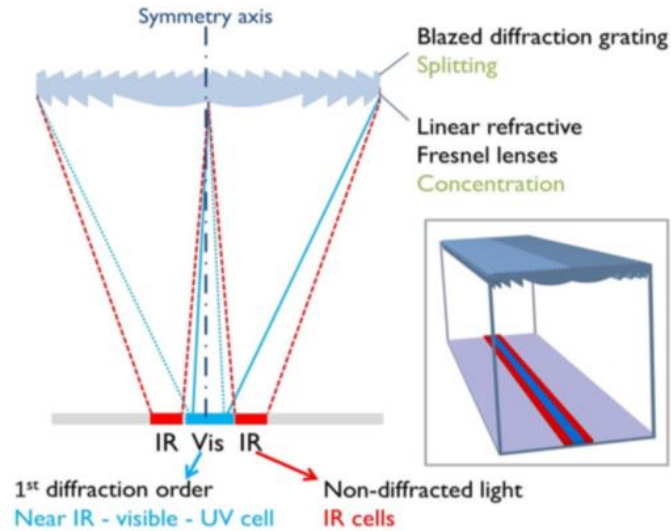


Figure 38. Local region on Fresnel lens. Diffraction grating and Fresnel lens with constant period were combined to spectrally separate and then focus light for solar cell application. Their data supports the idea that the focal length for the Fresnel lens proposed in this thesis for lens 1 will be shifted, resulting in a pinhole in the Fourier plane [28].

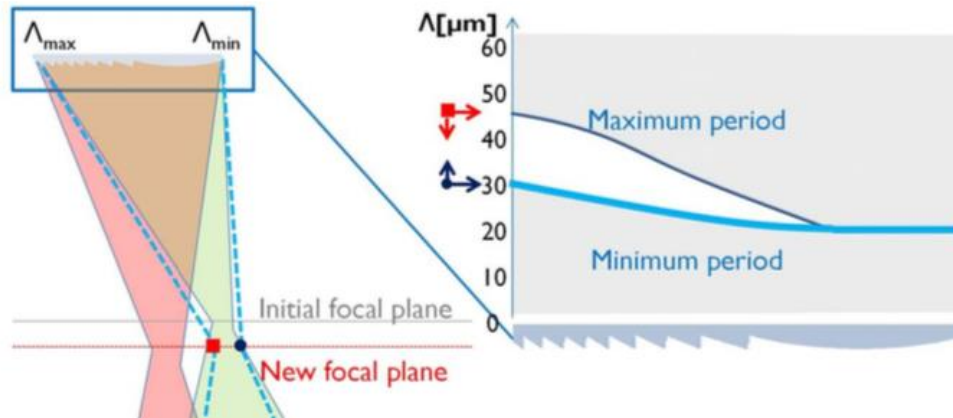


Figure 39. Shift in focal point of +1 order light. Céline Michel et. al proposed that by using a Fresnel lens with a spatially varying period, one can shift the diffracted light onto the same plane as the 0th order. This supports an important assumption made in this proposal [28].

7. Pinhole and Aperture Design

The pinhole and aperture can be created using metal deposition and grayscale optical lithography. They can be housed in a thin metal film on the scale of ten nanometers as was done in the solar concentrator example [29]. Fabricating the openings on the same substrate as the Fresnel lens introduces two new challenges to the DPM system: alignment with the Fresnel lens and eliminating reflections at the metal-glass interface. Alignment markers can solve the first issue, however, fixing the second will require more ingenuity.

Light incident on a material will either reflect, transmit, or be absorbed [30, 31]. For metals, transmissivity is zero because light is only reflected or absorbed. To prevent multiple reflections at the metal-dielectric interface, the author proposes selecting a metal with high absorption and low reflectivity for a desired wavelength while implementing either of the following two solutions: 1) create a multilayer metal-dielectric stack between the openings and the substrate, or 2) introduce surface texture by fabricating a moth's eye structure around the openings.

Reflectance at the interface is governed by the Fresnel equations. For transverse electric (TE)-polarized light,

$$R = rr^* = \left| \frac{\tilde{n}_q - \tilde{n}_m}{\tilde{n}_q + \tilde{n}_m} \right|^2, \quad (40)$$

where $\tilde{n}_q$ and $\tilde{n}_m$ are the complex refractive indices of the quartz substrate and metal, respectively. Equation 40 can be expanded by writing out the complex refractive index:

$$\Rightarrow R = \frac{(n_q - n_m)^2 + (k_q - k_m)^2}{(n_q + n_m)^2 + (k_q + k_m)^2}, \quad (41)$$

where n_q and n_m are the real parts of the complex refractive indices of quartz and a metal, respectively, and k_q and k_m represent the imaginary parts (i.e., the extinction coefficients). The reflectance at the metal-glass interface for gold (Au), nickel (Ni), and Chromium (Cr) are shown in Table 4.

Table 4. Reflectance at metal-dielectric interface for various metals.

Material	Refractive Index $\lambda = 633 \text{ nm}$	Extinction Coefficient	Reflectance
Gold	0.18344	3.4332	0.92
Nickel	1.99	4.1114	0.59
Chromium	3.1395	3.3152	0.42
Quartz	~ 1.5151	~ 0	N/A

Based on Table 4, chromium will surround the pinhole and aperture. Note that thin gold films have also successfully been sputtered onto a glass substrate [31]. Film uniformity on glass increased proportionally with deposition time; uniformity was constant for silicon. Gold adhesion will be discussed further in Section 8 when it is used to fabricate e-beam alignment marks for a Fresnel lens.

8. Macro- and Micro-DPM Implementation

As previously discussed in chapter 3, a DPM system consists of: 1) a light source; 2) a conventional microscope system composed of objective, collimator, condenser, and tube lenses; 3) a diffraction grating; 4) a 4f system; 5) a pinhole and an aperture in the Fourier plane; and 6) a camera (see Fig. 3 of Chapter 3). To improve the likelihood that the DPM on-chip system would function as intended, the author first installed components of a macro-system. Then elements were exchanged independently, replacing optics intended for the larger system with those that met the design requirements of the micro-scale system. Lastly, individual components were tested before combining the two modules that compose the micro-scale system.

8.1 Light Source

First, the light source was examined. Although a 650 nm laser with a specified maximum power of 30 mW was initially used in the setup, an interference pattern could not be observed. After reducing alignment error and seeing no effect on the collected image, the author reasoned that the issue was due to poor coherence and low output power of the laser. The laser used was a handheld visible fault locator with an unpolarized multimode fiber output port, but to achieve adequate coherence, the author used a single mode fiber (i.e., a spatial filter to increase spatial coherence), which significantly reduced the output power. In addition to wavelength, coherence and output power are important parameters of a chosen light source, particularly in instances in which a blazed grating is utilized. Such gratings function by diffracting 99% of transmitted light into the +1 order

while diffracting the remaining light into the 0th order. Although the +1 order is eventually filtered using a pinhole, it is still important for the 0th order light to have sufficient power. The magnitudes of both orders must be comparable to produce visible interference fringes with proper contrast in the camera plane.

Qualitatively, the original laser produced a uniform image. One could observe that light was incident on the camera; however, the features of the sample were indistinguishable. To quantify this result, a photodetector was inserted into the camera plane. The author determined that the laser was unreliable, producing fluctuating light and unexplained loss. The detected voltage was so small (i.e., on the scale of several mV, corresponding to micro watts of power considering the photodetector gain) that it was interpreted as noise. The author determined that the laser did not reach its specified maximum power of 30 mW after passing through the single mode fiber. To address this issue, the author integrated a new polarization-maintaining single mode fiber-pigtailed laser with an operating voltage of 2.45 V and an output power of 20 mW. The light-current-voltage (LIV) curve for the purchased 642 nm laser is shown in Fig. 40. Note that the system is typically used within 8 – 12 mW while imaging in the Photonics Systems Laboratory.

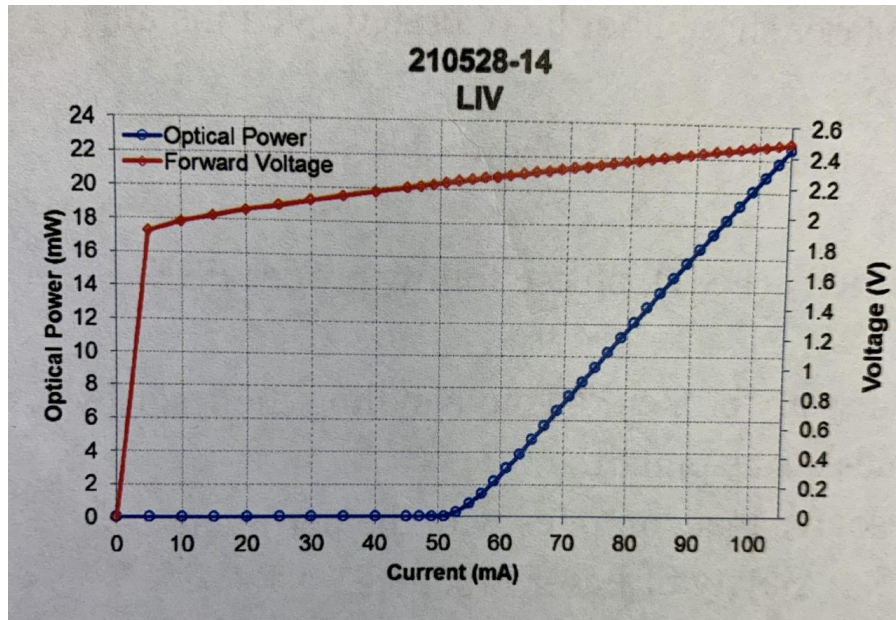


Figure 40. LIV curve of the single mode laser at 25C. The threshold current is 50 mA and typical operating current is 82 mA.

Assembly of the new Thorlabs laser was required. First, the fiber-coupled laser was connected to a Thorlabs LDM9LP laser mount based on a pin code A configuration (see Fig. 41). Next, the laser mount was connected to a temperature controller (i.e., TEC driver) and a laser diode current controller (i.e., LD driver) to ensure that it would produce a reliable output; the LD and TEC drivers were housed within the same instrument, an ILX LDC 3700. Because the ILX LDC 3700 was manufactured by a different company, it was incompatible with the laser mount, making it necessary to incorporate three adapters between the two systems for proper functionality. The first was a hybrid output cable with nine pins that was connected to the ILX instrument. The next two originated from a single male-to-female adapter that was cut, forming two adapters with frayed ends (referred to as PSL adapters in Table 5). The female end was inserted into the TEC driver, and the male end was inserted into the LD driver. The wire color associated with each used pin was

noted. As a result, proper connection between the laser mount pins (via the PSL adapters) and the laser diode controller could be implemented.



Figure 41. Laser mounting module from Thorlabs.

Table 5. Laser cable adapter.

Hybrid Output Cable	ILX Input	Thorlabs LDM9LP	PSL Adapter
1	TE module (+)	TEC pin 4	TEC yellow
2	TE sensor (+)	TEC pin 2	TEC bright red
3	Not Connected		
4	PD Anode (-)	LD pin 4	LD yellow
5	Laser Anode	LD pins 8 and 9	LD gray (8), black (9)
6	TE module (-)	TEC pin 5	TEC green
7	TE sensor (-)	TEC pin 3	TEC orange
8	PD Cathode (+)	LD pin 2	LD bright red
9	Laser Cathode	LD pins 6 and 7	LD blue (6), purple (7)

8.2 Grating

Next, a blazed grating with 3.33 μm period was integrated into the conjugate sample plane of the conventional microscope. The 24.8-degree blaze angle was chosen such that

for 633 nm light, there was maximum transmission efficiency into the +1 order while that into the 0th order was nearly zero (see Fig. 42).

Figure 43 demonstrates the functionality of the grating. One can observe light diffracted into multiple orders but note that the +1 and 0th orders are the only ones of interest for DPM. The 0th order has the lowest intensity while the +1 order contains more light than any of the diffracted orders. Its theoretical value is 99%, but its experimental value was approximately 65% due to power diffracted into the other orders (e.g., -2, -1, 0, +2, +3, etc.). As the light travels along the optical axis, all orders continue to separate spatially. They focus to distinct spots that are spatially separated in the Fourier plane.

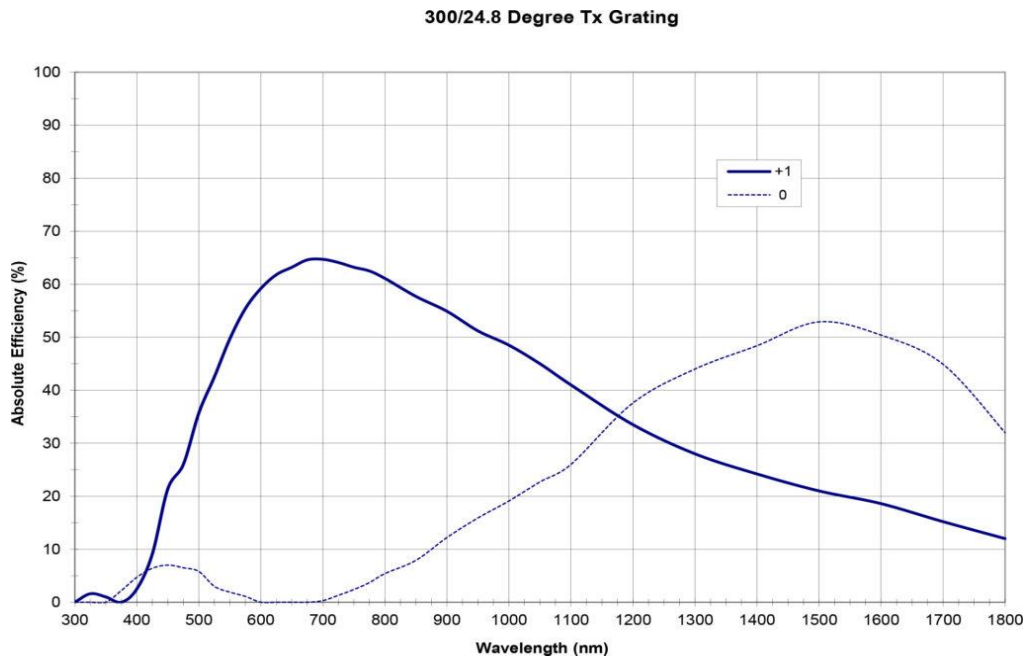


Figure 42. Diffraction efficiency of blazed grating from Dynasil.

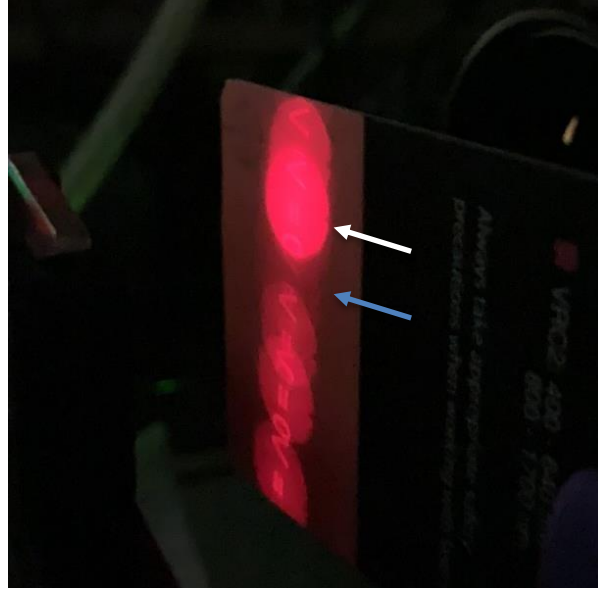


Figure 43. Multiple image copies produced by diffraction grating. Multiple image copies are produced by a commercial diffraction grating. The 0th order appears at the center of the detection card and is shown with the blue arrow. The white arrow shows the +1 order.

8.3 Pinhole and Aperture Alignment for Macro-DPM

To align the pinhole and aperture associated with the macro-setup, the author used a custom-machined metal adapter that included an appropriately sized 6 mm aperture for the 0th order and an opening 14.5 mm away for a custom-machined pinhole housing. After discovering literature on the translation stage specifications of sub-micron positioning accuracy with the Thorlabs ZST225B actuators, the author manually aligned the pinhole; afterwards, LabVIEW software was utilized to improve alignment accuracy.

To ensure safety, the alignment procedure was executed at a 55 mA current, resulting in an output power of approximately 0.5 mW. A laser detection card was translated along the optical axis to estimate the Fourier plane (i.e., the plane where the two beams focused). The x- and y-coordinates corresponding to where the +1 order focused were specifically

noted because aligning the pinhole to this beam would prove more difficult than aligning the 0th order to the larger aperture. Next, the pinhole/aperture adapter, which was attached to an automated translation stage allowing precise adjustments in three orthogonal directions, was inserted into the Fourier plane.

Initially, the laser beam fell on the pinhole housing rather than the pinhole center. Because the area near the pinhole center was surrounded by black-anodized aluminum to prevent back reflections, it was challenging to determine the exact beam location within a few millimeters of the pinhole. The author determined a more accurate pinhole location by placing a flashlight flush against the pinhole housing while the laser was turned off. The pinhole location relative to the edge of the black aluminum was noted before powering on the laser. The pinhole/aperture adapter was then translated by tens of microns in x and y while the author observed the effect on the light intensity from the camera side of the setup (see Fig. 44). The translation stage was fixed at the x and y coordinates (in millimeters) corresponding to the brightest beam (22.8, 16.2). This resulted in a proper interference pattern at the camera plane (see Fig. 45). Current was set to 82 mA to obtain the image of a Thorlabs reflection target coated by the author with 10 nm of chromium for adhesion and 40 nm of gold.

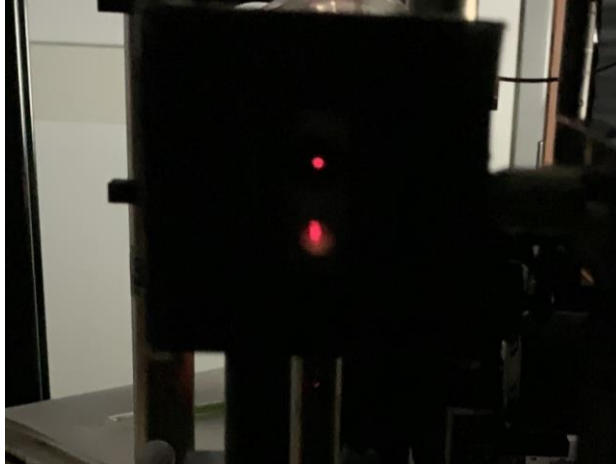


Figure 44. Pinhole and aperture alignment. The view from the camera side of the pinhole and aperture at the optimal (x,y) position. The +1 order beam is visible through the 10 μm pinhole on top while the 0th order beam is visible through the aperture below.

The z-coordinate of the stage was later optimized by utilizing a cross-sectional indicator graph in LabVIEW. The cross-section taken with the Hamamatsu camera provided a one-dimensional representation of the fringes produced by the interferometer (see Fig. 45). A zoomed-in image of the fringe pattern taken with the Amscope camera is shown in Fig. 46. The effect that translations in z had on the magnitude of the fringes was observed. Z-coordinates producing aperiodic outputs were avoided. The optimal z-coordinate of 7.07 mm was determined.

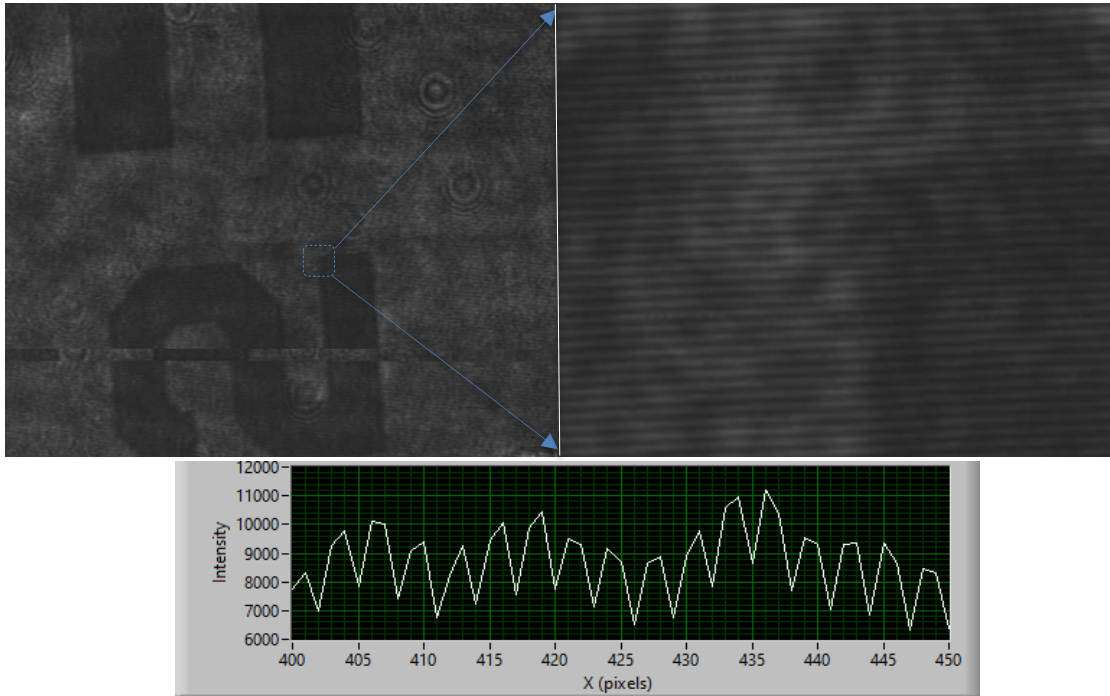


Figure 45. DPM image of Thorlabs reflection target. Sample coated with 10 nm of Cr and 40 nm of Au by author for imaging. Image taken with Hamamatsu camera. Proper fringes are visible after aligning the macro-DPM setup. Cross-section of fringes obtained with LabVIEW.

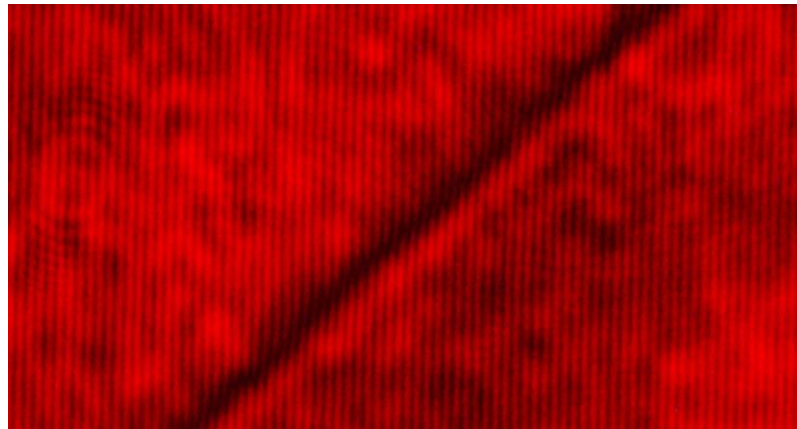


Figure 46. DPM Fringes. Enlarged image of Thorlabs reflection target that shows fringe shift associated with height change across a sample. Image taken with Amscope camera.

8.4 Hamamatsu vs. Amscope Camera

As mentioned in chapter 3, proper sampling is a DPM requirement. The grating period and camera pixel size must meet design constraints to maintain the resolution of the system. In our case, we chose the grating period, $\Lambda = 3.33 \mu\text{m}$, first because of the wide commercial availability of gratings with this period. Viewing Equation 12, one can see how the grating period relates to multiple parameters, including the $4f$ magnification of the system, pixel size, numerical aperture/magnification of the objective lens, and wavelength. Of those parameters, the author considered varying $4f$ magnification and pixel size; however, with DPM on-chip, the author is limited in varying the $4f$ magnification because lens 1 is affixed to a substrate on which light must come to a focus. Essentially, the Fourier plane resides on the substrate, so substrate thickness must match the focal length of lens 1. Nonetheless, there is limited flexibility adjusting the focal length and, thus, the $4f$ magnification because quartz substrates are typically manufactured with only specific thicknesses, such as 1 mm and 3 mm.

Quartz substrates with 1 mm thickness are often used as microscope slides, and those with 3 mm thickness are used as photolithography masks. The latter was used for DPM on-chip, resulting in a $4f$ magnification of 1 (i.e., $f_1 = f_2 = 3 \text{ mm}$). Using Equation 12, one can determine that pixel size must be less than $1.38 \mu\text{m}$ for the camera to properly sample an object with Design #2. To verify that the interferometer functioned properly before the on-chip device was fully fabricated, a black and white Hamamatsu ORCA-ER-1394 camera with a $6.45 \mu\text{m}$ pixel size was used in the macro-system with larger optics (i.e., $f_1 = 75 \text{ mm}$, $f_2 = 400 \text{ mm}$). To meet DPM on-chip requirements, the Hamamatsu was replaced with an Amscope MU1803-HS camera with a $1.25 \mu\text{m}$ pixel size (see Fig. 47). The Amscope

camera is capable of color sensing although this color information is not useful when using a monochromatic source. The Amscope camera spans 6.14 mm by 4.61 mm. Due to color saturation, the current was reduced to 70 mA during imaging.

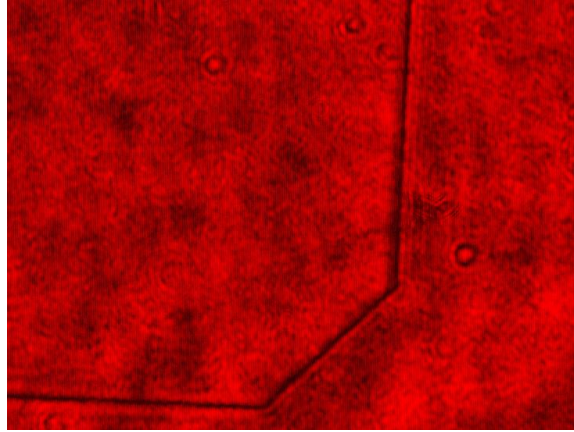


Figure 47. DPM image of Thorlabs reflection target taken with Amscope MU1803-HS camera.

To understand the effect of the camera, interference images were taken using macro-DPM optics with the Hamamatsu and Amscope cameras. The fringe contrast ratio of 2:1 is comparable for the two cameras (see Figs. 45 and 48). This is to be expected because the contrast ratio is a property of the interference pattern and not the camera. However, there is a notable difference in the numerical values because the Amscope camera is limited to 8 bits (0-255) per color channel and 8 bits after grayscale conversion. On the other hand, the Hamamatsu camera acquires images that are 12 bits (0-4095), which get automatically rescaled to images with 16 bits (0-65535) for saving as standard 16-bit TIFF images. There is also a 5x decrease in the fringe frequency associated with the Amscope camera because of its 5x smaller pixel size.

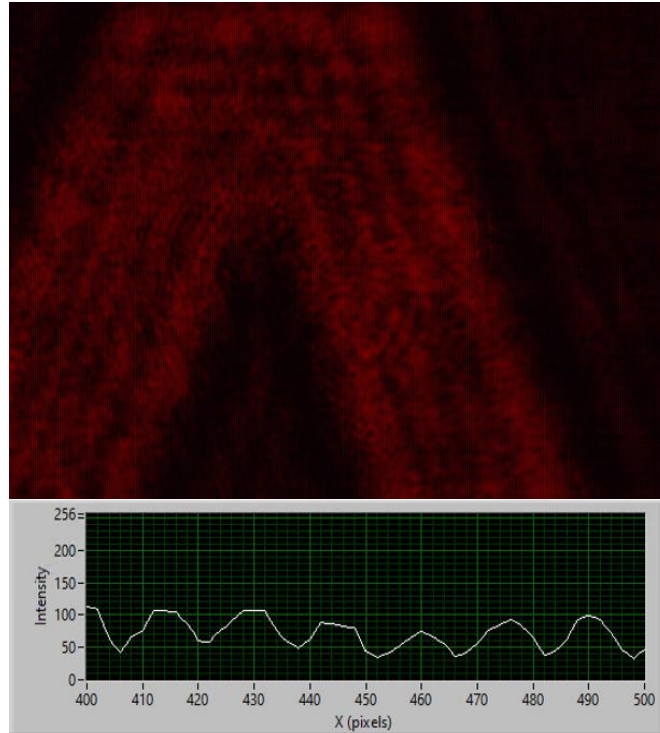


Figure 48. DPM image of microscope calibration slide taken with Amscope MU1803-HS camera. The cross-section of the image was obtained using LabVIEW. Note that for certain combinations of image viewing size and display resolution, there can be Moiré effects in which the period appears to be quite different than when the image is fully zoomed. The cross-sectional slice allows viewing of the true interference period.

One might notice that the cross-sections shown in Figs. 45 and 48 correspond to different samples. The data was extracted before macro-DPM was converted into a micro-DPM setup. To gain more insight regarding how pixel width variation might affect a DPM system, the author imaged the same calibration slide with both cameras. Results are discussed in the next section.

8.5 Image Processing with Matlab

Image processing for DPM was executed in Matlab. The author will first discuss the results for the macro-system before showcasing those for the on-chip system. Note that the code remains unchanged for both cases; however, the field of view and resolution varies between the two systems.

Before processing, it was necessary to obtain two images with the interferometer: a calibration image consisting of a uniformly flat region of the sample and an image that included the region of interest containing features. To start, one can take the Fourier transform of the latter. When using a camera capable of imaging colors, it is necessary to convert into a grayscale version before taking the Fourier transform. Because a 642 nm laser was used in our case, the red color channel was extracted and used for the grayscale image. The full Fourier transform of an image captured by the system is shown in Fig. 49 in black and white to allow easier viewing. All three diffraction orders are centered about the three brightest spots in the figure, with the +1 order being to the right of the 0th order. The built-in `fftshift` function was used to shift the 0th order from the top left corner to the center of the screen for viewing purposes. Next, the pixel position of the +1 with respect to the 0th order was determined. The simplest way is to zoom into the brightest pixel associated with the 0th order and the +1 order and note the locations. Finally, one can compute the parameters in Table 6 that serve as input parameters for the code that will output structure heights.

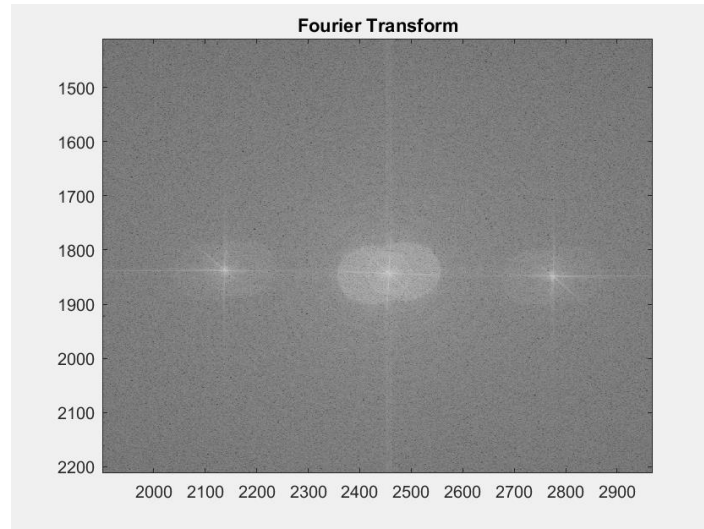


Figure 49. Fourier transform of object captured by DPM. Image processing was executed in Matlab. The lobe of interest is located at the far right of the transform.

Table 6. Post-processing parameters. Six input parameters required to compute the height of a DPM image.

Parameters	Definition
N	Number of pixel columns
M	Number of pixel rows
v_0^*	Distance between k_x -coordinates of pixels associated with the 0th and +1 orders
u_0^*	Distance between k_y -coordinates of pixels associated with the 0 th and +1 orders
D^*	Radius of the filter in the frequency domain (taken to be $v_0/3$ for simplicity)
λ	wavelength

After determining the inputs in Table 6, one must create a mask that contains a circular region with radius D around the +1 order in the frequency domain to ensure that the correct region of interest is captured (see Fig. 50). An inverse Fourier transform is performed providing an output in the space domain. The result is an output $Z = A(x,y) \cdot e^{i\beta x + \phi(x,y)}$, where $A(x,y)$ represents image amplitude, β is the modulation frequency of the grating, and $\phi(x,y)$

is the desired phase to be recovered. This process is repeated for the calibration image and the output Z of a calibration image is measured and stored into a variable where the amplitude and phase for the background are both assumed to be constant. From the Z variables for the sample and the background, one can extract the phase and amplitude information of the sample by dividing and saving the argument and amplitude of the result, respectively. Because the phase is wrapped (see Fig. 51a), it is necessary to execute an unwrapping algorithm for accurate results (see Fig. 51b). Lastly, because we operated in reflection mode, we had to perform the Equation 7a in order to compute final height results (see Fig. 51c). Within Matlab, it is possible to use data cursors to learn the height associated with each pixel. In this case, pixel values ranging from 130 nm to 180 nm were obtained. To determine an accurate portrayal of the height, one must average the height over regions (see Fig. 52). The resulting net height was 161 nm for the two rectangular regions shown. A Dektak profilometer was used verify DPM results (see Fig. 53) and shows an average height of 161 nm. Therefore, there is excellent nanometer level accuracy and consistency between the two methods. For DPM, because of a possible global phase unwrapping error, the recovered height can be incorrect by an integer multiple of half-wavelengths in reflection mode. Thus, Fig. 52 and subsequent figures report two possible values for the height difference.

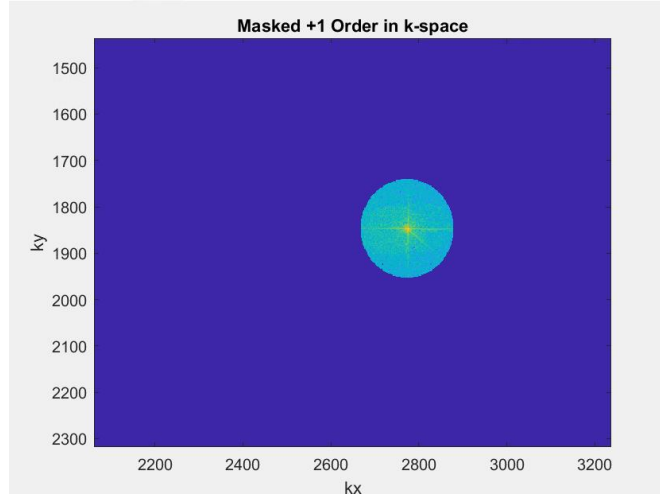


Figure 50. Masked +1 order in k-space. The fftshift function in Matlab was used to bring the Fourier transform to center screen. A mask of radius D was applied to the region associated with the +1 order.

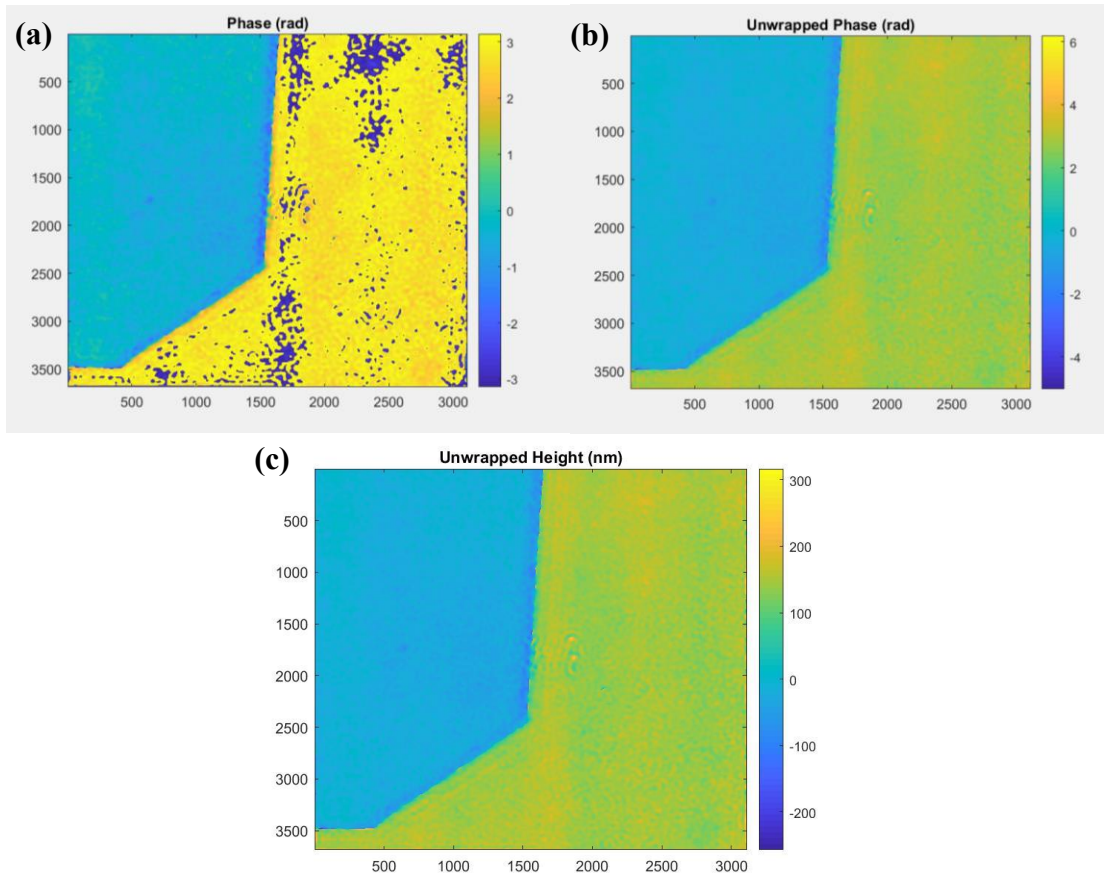


Figure 51. Post-processing results of Matlab program. (a) Wrapped phase in radians, (b) unwrapped phase in radians, and (c) unwrapped height in nm.

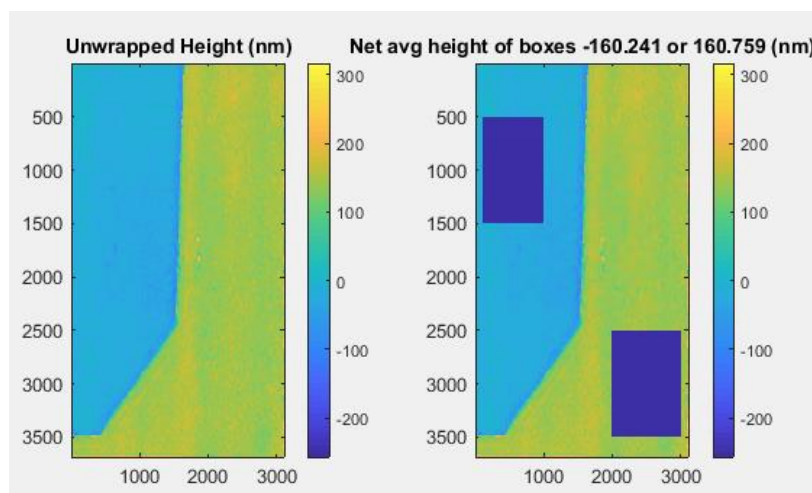


Figure 52. Plots displaying unwrapped height along with crop regions useful for height averaging.

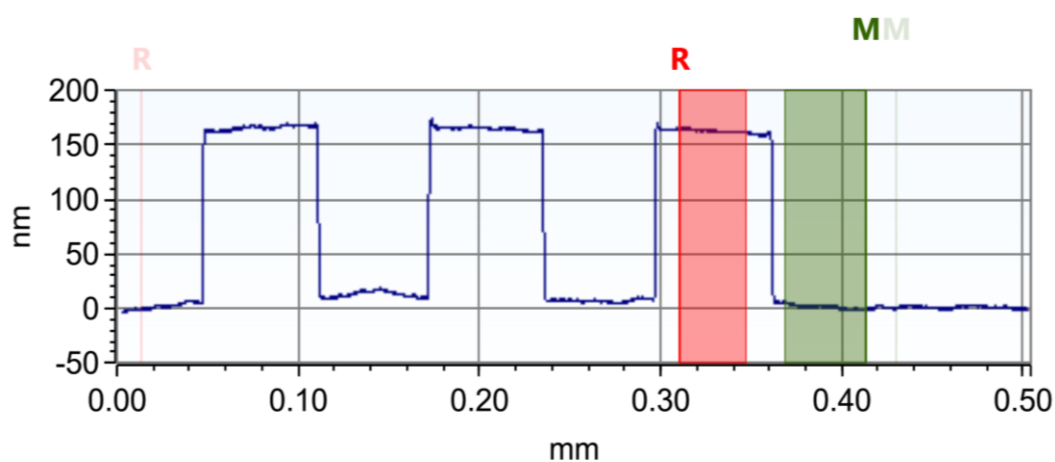


Figure 53. Profilometer results of coated Thorlabs reflection target. Height difference is calculated after Dektak system averages values over two regions. Step height is 161 nm. Profile obtained by Lonna Edwards and Karthick Jeganathan.

The calibration slide containing the letter “V” was imaged with the Hamamatsu camera and the Amscope camera (see Fig. 54). Note that Amscope camera is mounted rotated by 90 degrees relative to the Hamamatsu because of the location of the mounting screws. Height values were averaged over two regions for each sample. The resulting structure height was 232 nm for the Amscope camera and 238 nm for the Hamamatsu camera. Note that the horizontal line shown in the Hamamatsu image is a defect due to pixels that no longer work. Additionally, there appears to be phase wrapping issues that occur with the Amscope camera but not with the Hamamatsu. This may be due to a large portion of the elevated structure traversing the edges because the FOV is reduced with the Amscope camera. Figures 55 – 57 show comparisons of the two cameras throughout image processing.

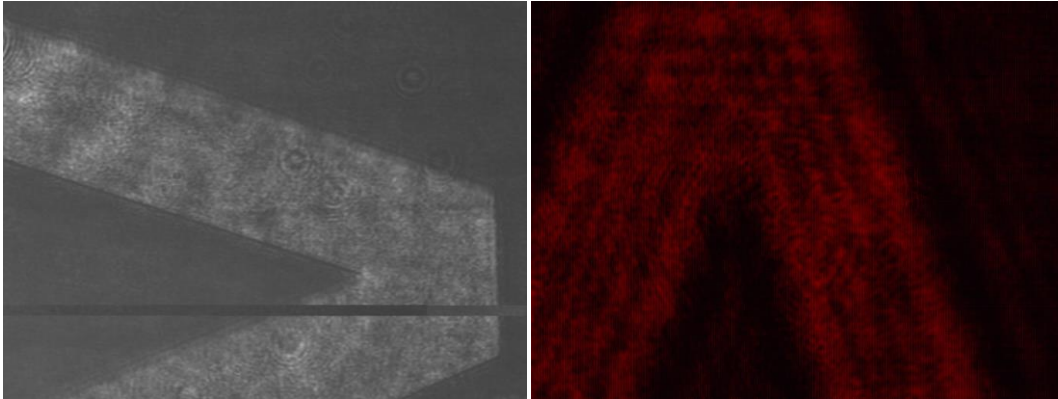


Figure 54. Images of a calibration slide taken with two cameras. The Hamamatsu image is shown on the left, and the Amscope is shown on the right. Malfunctioning pixels create the horizontal line on the former.

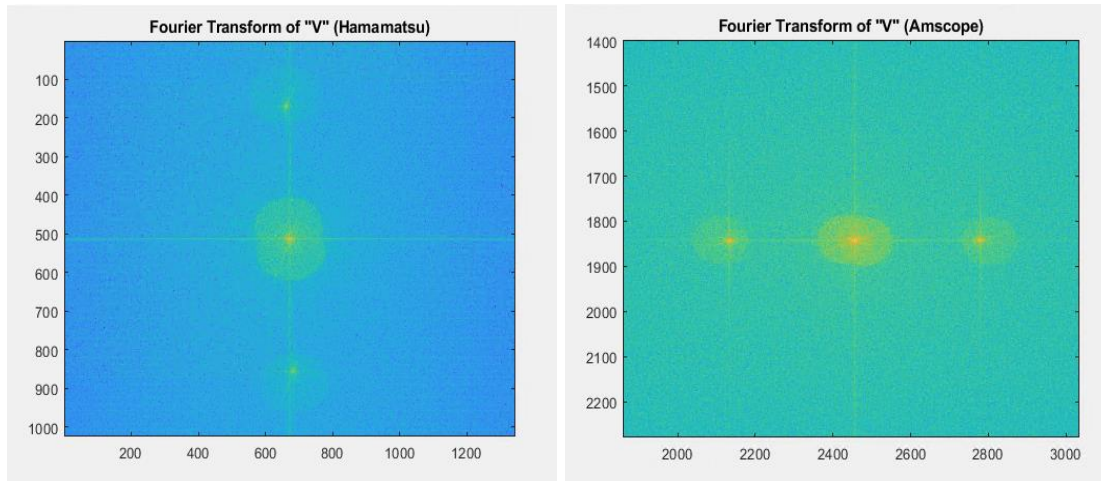


Figure 55. Fourier transforms of the Hamamatsu image (left) and the Amscope image (right).

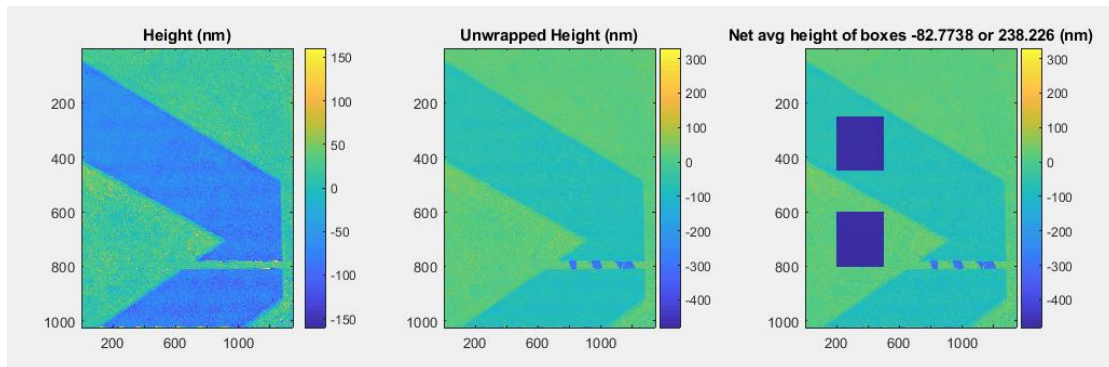


Figure 56. Post-processing results obtained for the Hamamatsu camera. The average height of the raised structure was computed as 238 nm using the original macro-DPM camera.

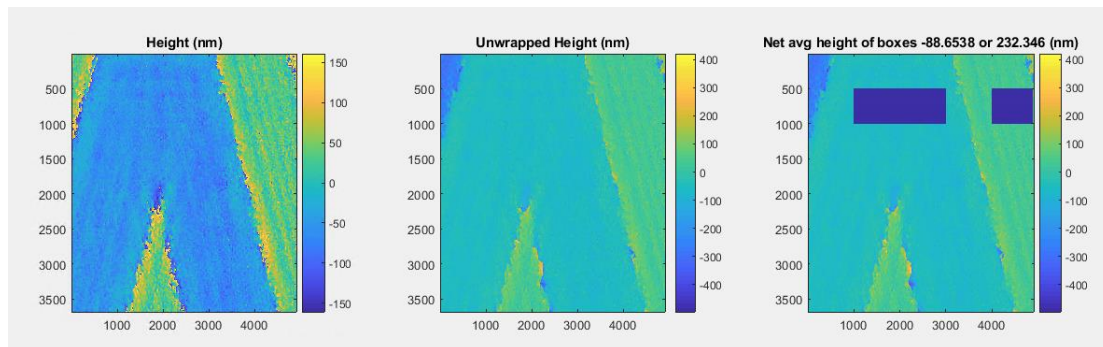


Figure 57. Post-processing results obtained for the Amscope camera. The average height of the raised structure was computed as 232 nm using the new camera.

8.6 Fresnel Lens Fabrication: Edmund Optics vs. HMNTL

The Fresnel lens is an extremely important optical element that makes DPM on-chip feasible. Its compact structure is advantageous not only due to less material consumption but also because it inherently reduces absorption losses. Additionally, Fresnel lenses have the advantage of reducing spherical aberrations when one uses it in the preferred orientation: In this instance, the grooved surface is directed towards a collimated beam. It is still possible for a Fresnel lens to function with the grooves facing the opposite direction; however, the effects of misalignment are more significant (i.e., more spherical aberrations occur).

Two approaches were taken to integrate the Fresnel lens on-chip. One involved purchasing pre-made lenses with $NA = 0.93$ and $f = 3$ mm from Edmund Optics. The second approach involved fabricating a Fresnel lens in the Holonyak Micro- and Nanotechnology Laboratory (HMNTL) utilizing electron beam lithography. While the Fresnel lenses manufactured by Edmund Optics (see Fig. 58) consisted of blazed structures and, thus, an associated theoretical efficiency of 99%, those fabricated at HMNTL consisted of eight binary steps. The theoretical efficiency of the latter is 95%. Considering the difficulty of fabricating a continuous structure versus eight binary steps, we determined that the 4% reduction in efficiency was permissible.

To fabricate the 8-step lens, we first created a script in Matlab to compute zone radii. The outer radii for the concentric rings in the first 2π zone are shown in Table 7. Next, we grouped concentric rings into their appropriate layers (i.e., steps 1, 9, 17, etc. formed the first layer). Eight total layers were imported into AutoCAD to form the complete structure.

Lastly, the CAD file was imported into BEAMER software for format conversion. Figure 59 shows the desired Fresnel lens structure displayed in AutoCAD.

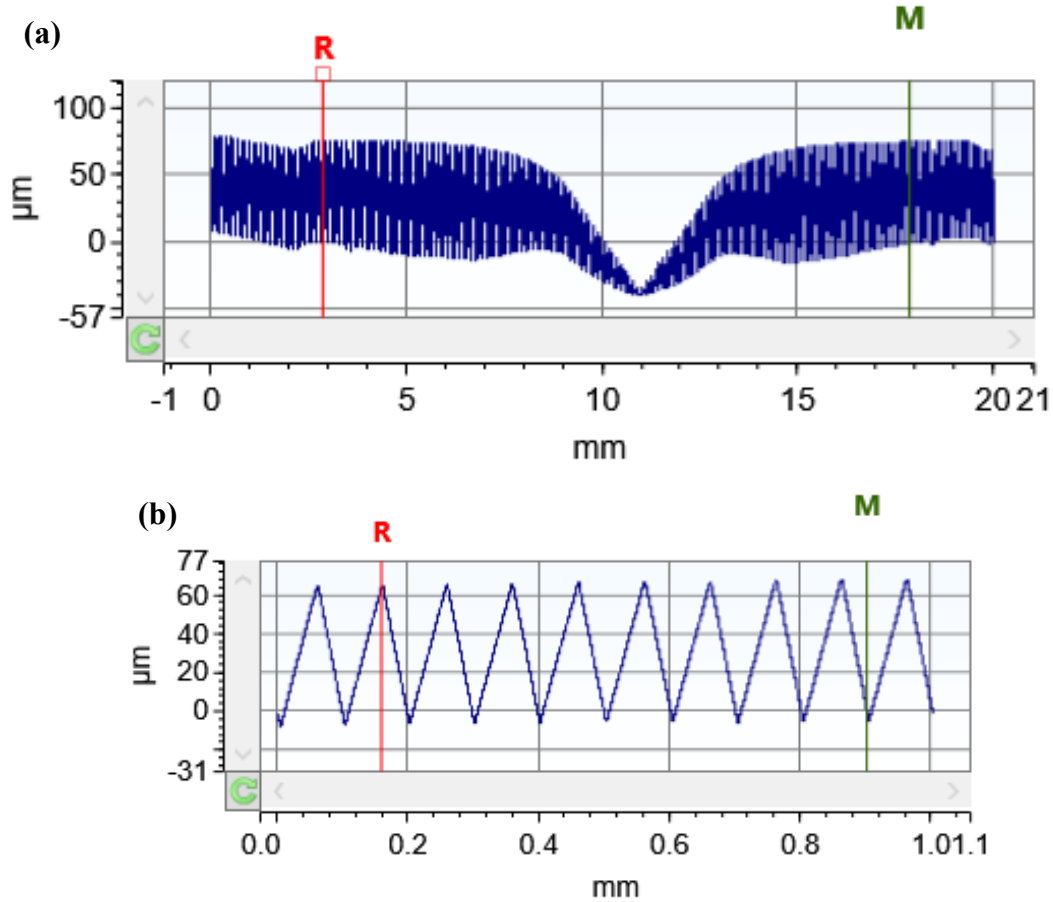


Figure 58. Edmund Optics Fresnel lens. (a) Profile of a Fresnel lens with a 5 mm focal length. Scan length was 20 mm. (b) Enlarged view of sample showing a 70 μm step height. Profile obtained by Lonna Edwards and Karthick Jeganathan.

Table 7. Computed radii for first 2π zone of a Fresnel lens with N=8 steps. This lens was created for Design #2.

Step	Outer radius [μm]
1	21.8
2	30.8
3	37.7
4	43.6
5	48.7
6	53.4
7	57.6
8	61.6

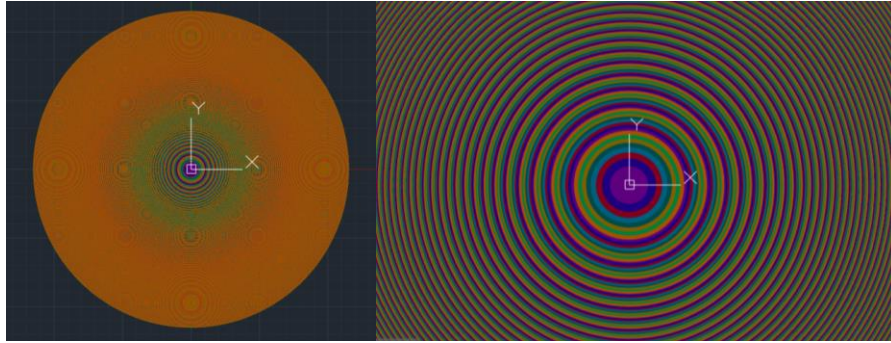


Figure 59. AutoCAD mask for the HMNTL Fresnel lens.

Initially we considered fabricating the lens in quartz using e-beam lithography and reactive ion etching; however, it seemed more efficient to utilize a resist that could also function as lens material. This would eliminate the need to etch an already limited substrate thickness. HSQ resist is often used in e-beam lithography due to its superior resolution, and the ability to vary its refractive index post-exposure. Nonetheless, we determined that PMMA was the optimal choice for DPM on-chip. At 642 nm, its refractive index is approximately 1.48 compared to the standard of 1.4 for HSQ. Because the substrate material has a refractive index of 1.46, PMMA matched the index more closely. PMMA was also capable of surpassing the height limitations of HSQ without sacrificing lateral

resolution. Table 8 shows the desired step heights of our structure. Note that while the total height of each 2π zone is $1.376\ \mu\text{m}$, the eighth step is within the substrate.

Table 8. Step heights of each layer of HMTNL Fresnel lens.

Layer	Step Height
1	$1.204\ \mu\text{m}$
2	$1.032\ \mu\text{m}$
3	$860\ \text{nm}$
4	$688\ \text{nm}$
5	$516\ \text{nm}$
6	$344\ \text{nm}$
7	$172\ \text{nm}$
8	Within substrate

The process of fabricating a Fresnel lens with e-beam lithography requires characterization. One must determine the proper exposure dosage for each step height. During this process one must counter the proximity effect that occurs when an exposure dose intended for one area spreads into a neighboring region. Fortunately, proximity effect correction can be implemented in Beamer.

Lenses were patterned using the following base doses in uC/cm^2 : 500, 600, 700, 800, and 900 (see Figs. 60 – 62). Note that changes in the exposure time at each pixel enabled gray-scale lithography on samples. While we were able to achieve a total PMMA thickness of $1.293\ \mu\text{m}$ and a single step of height $223\ \text{nm}$, we were unable to fabricate the remaining six steps. Each step should have a height of $172\ \text{nm}$. Instead, the structure tapered after the first step.

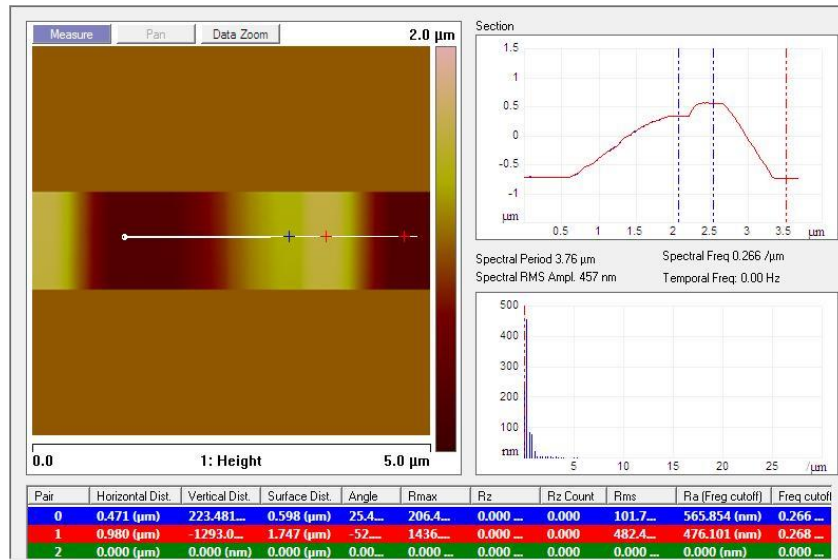


Figure 60. HMNTL Fresnel lens fabricated with the Elionix ELS-G150. A single step was fabricated correctly using the CAD file designed by the author. Dr. Edmond Chow used a base dose of 500 uC/cm² on this sample with a resist thickness of 1293 nm and a 223-nm step height.

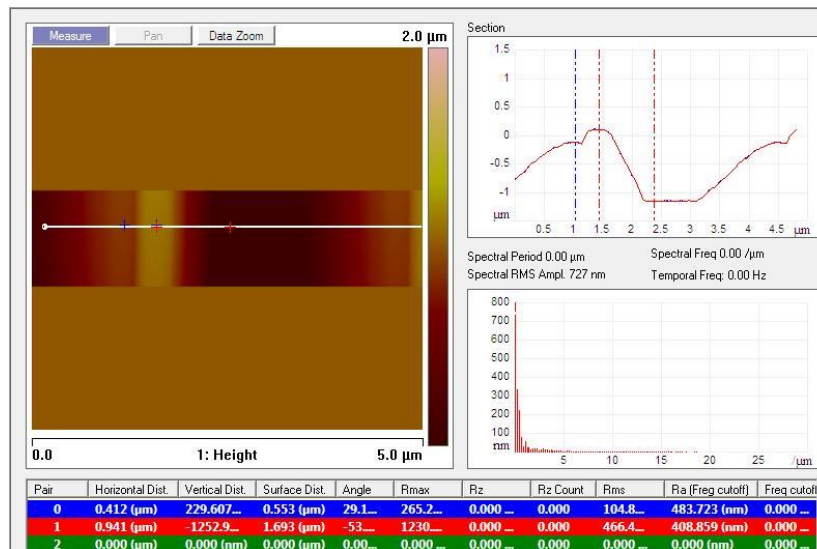


Figure 61. HMNTL Fresnel lens fabricated with the Elionix ELS-G150. A single step was fabricated correctly using the CAD file designed by the author. Dr. Edmond Chow used a base dose of 700 uC/cm² on this sample with a resist thickness of 1252 nm and a 229-nm step height.

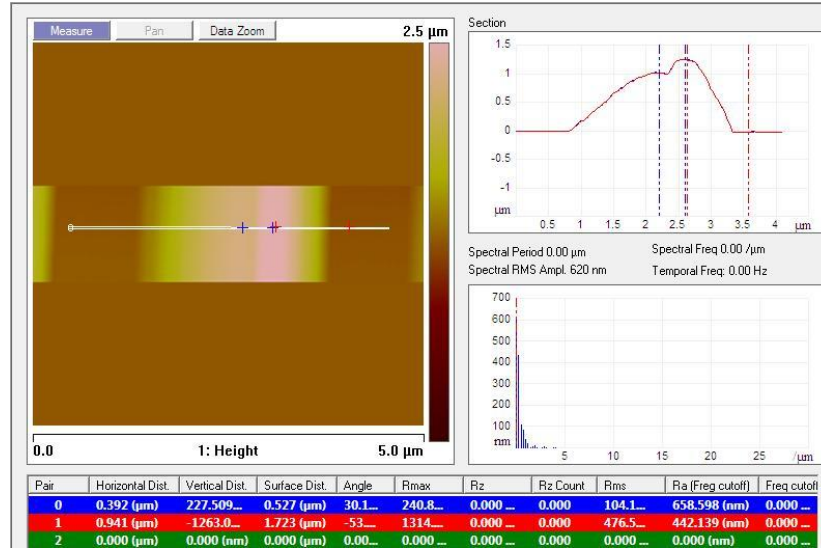


Figure 62. HMNTL Fresnel lens fabricated with the Elionix ELS-G150. A single step was fabricated correctly using the CAD file designed by the author. Dr. Edmond Chow used a base dose of 900 $\mu\text{C}/\text{cm}^2$ on this sample with a resist thickness of 1263 nm and a 227-nm step height.

8.7 Pinhole and Aperture Fabrication

In the field of optics, system alignment is critical for quality performance. For DPM, aligning the pinhole and aperture with respect to the 4f system with minimal error is required. The 0th order should pass through the center of both lenses. Additionally, the pinhole and aperture must reside one focal length from lens 1 to properly capture and filter the 0th and the +1 order, respectively. Fortunately, with free-space optics there is flexibility to adjust the position and rotation of elements at any time for improvement. When creating an on-chip device, however, there is no flexibility after the initial alignment.

While it is possible to keep micro-scale DPM optics separate by increasing the lens focal length, this increases the system size and makes the portable applications less practical. Separating the optics also has the disadvantage of the system becoming misaligned if it is

slightly bumped. One might easily misalign the closely packed, thin diffractive elements that modify light on such a small scale. As a result, our solution to create a system with a pre-aligned robustly packaged Fresnel lens is advantageous. We developed two recipes to integrate the pinhole and aperture with a Fresnel lens depending on whether an Edmund Optics or HMNTL lens was used. Both recipes are discussed below.

8.7.1 Pinhole and Aperture Fabrication with Edmund Optics Lens

The recipe for the substrate combined with the Edmund Optics lens required fewer steps than that of the HMNTL lens. This is because the former case involves a one-time manual alignment post-processing while the latter is aligned during lithography. In both instances, a 5" X 5" quartz substrate with 3 mm thickness was used. The company Nanofilm deposited an 80 nm layer of blue reflective chromium on the surface followed by 0.53 μm of AZ 1518 photoresist. Blue reflective coating was chosen to reduce the amount of light reflected back into the system when $\lambda = 642 \text{ nm}$. Looking at Fig. 63, one can see that the reflectance is approximately 3% for that wavelength. It is critical to reduce back reflections in a DPM system because they negatively affect image quality.

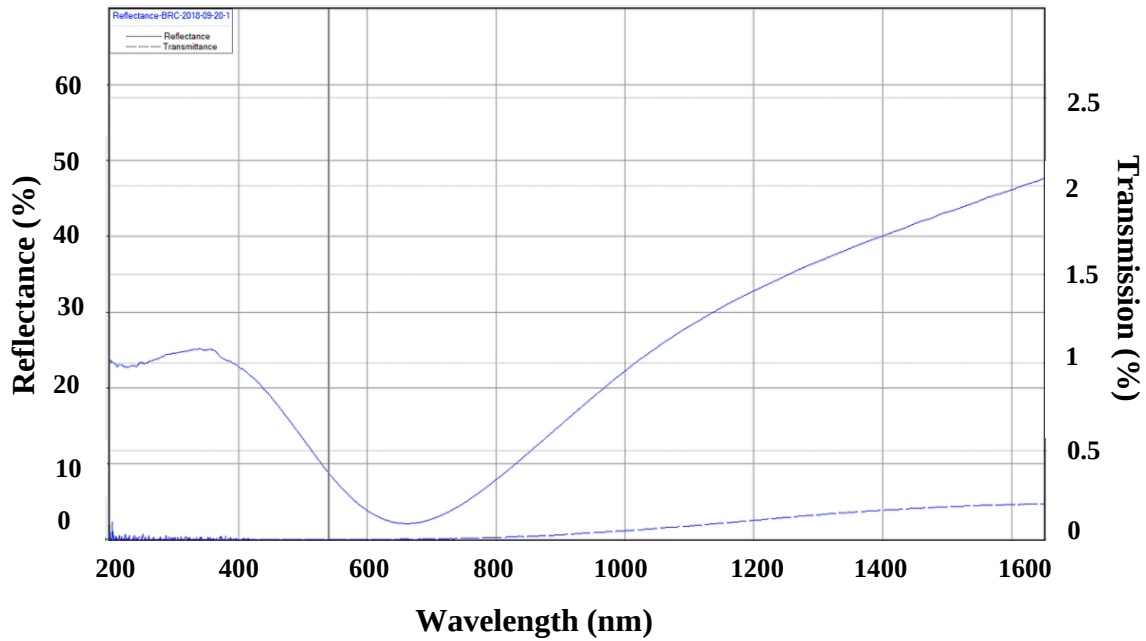


Figure 63. Reflectance and transmittance of blue-reflective chrome substrate from Nanofilm.

The author tested both the Heidelberg uPG 101 and the Heidelberg MLA150 to determine the best instrument for substrate patterning. After trial and error, the latter was used to pattern the pinhole and aperture. Compared to the former, this system utilizes a micro-mirror array with a laser to pattern substrates as large as 6” during the same exposure, eliminating the need to break CAD masks into quadrants for multiple exposures. It also removed the need to swap write-heads to reduce exposure time. These benefits were possible without sacrificing resolution and quality.

The author patterned 16 samples on a single substrate that included some variation of three parameters: pinhole diameter, aperture diameter, and separation distance. The author fabricated several samples with magnified pinhole and aperture diameter to ensure that the

+1 and 0th order beams were captured even if there was a mismatch between the theoretical separation distance and what was observed experimentally. In case the calculated separation distance of $d_x = 0.587$ mm was incorrect, the author also included cases for $0.75d_x$ and $1.25d_x$, respectively. The 16 combinations chosen are shown in Table 9. With this intentional parameter variation, the author increased the odds that one of the samples would function properly within the setup. The AutoCAD mask of the substrate is shown in Fig. 64.

Table 9. Pinhole and aperture parameters for the 16 DPM on-chip substrates.

Array Name	Pinhole Magnification	Aperture Magnification	Separation Distance [mm]
A	1	1	0.587
B	1	1	0.570
C	1	1	0.440
D	1	1	0.734
E	1	2	0.570
F	1	2	0.587
G	1	2	0.734
H	2	1	0.587
I	2	1	0.570
J	2	1	0.440
K	2	1	0.734
L	2	2	0.570
M	2	2	0.587
N	2	2	0.734
O	1	1	0.500
P	1	1	0.650

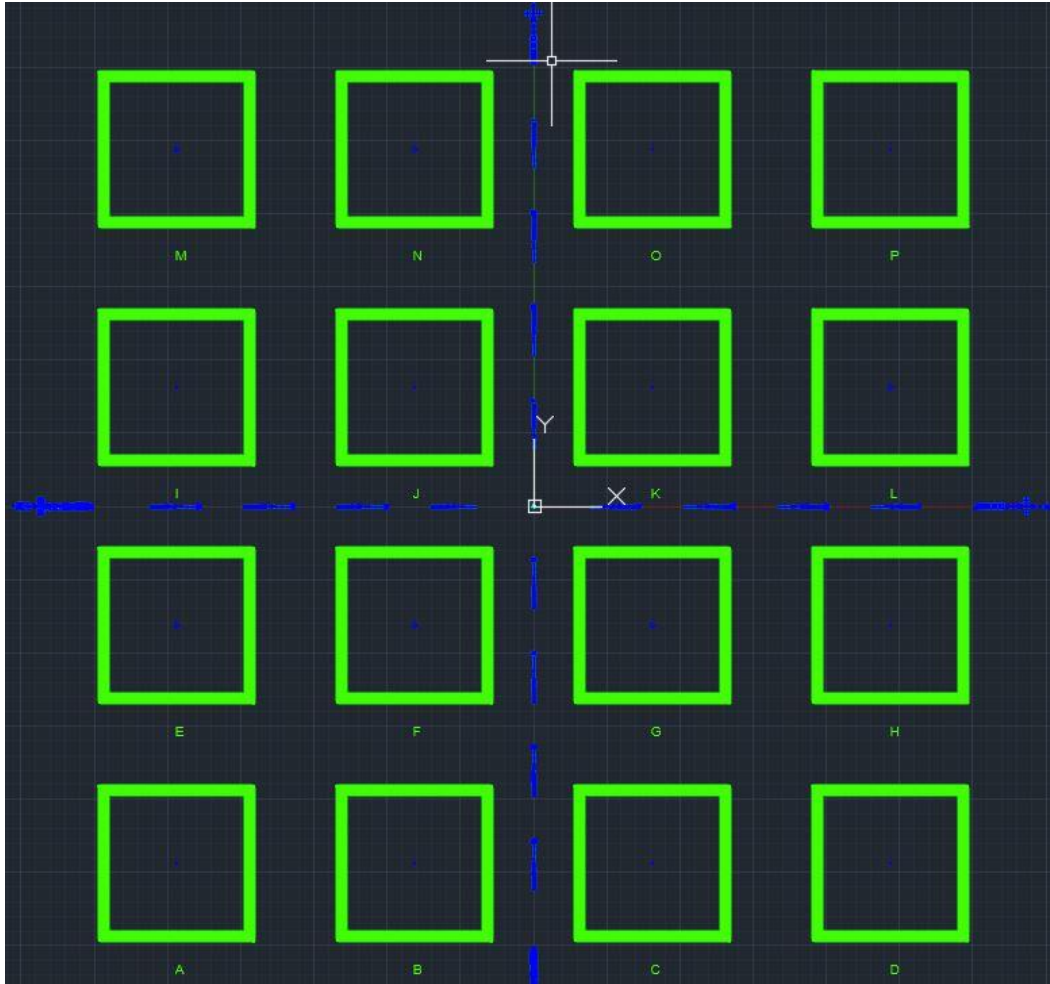


Figure 64. AutoCAD mask of 16 DPM on-chip substrates.

The mask pattern was exposed with an exposure dose of 60 mJ/cm^2 and defocus of -3 . These optimized values were determined after implementing the dose test procedure described previously. Next, the sample was developed in a 1:4 ratio of AZ 340 developer to water for 30 seconds. Lastly, the chromium was etched for 32 seconds. Photoresist was removed using acetone and isopropyl alcohol. A camera photo of the 16 samples is shown in Fig. 65.

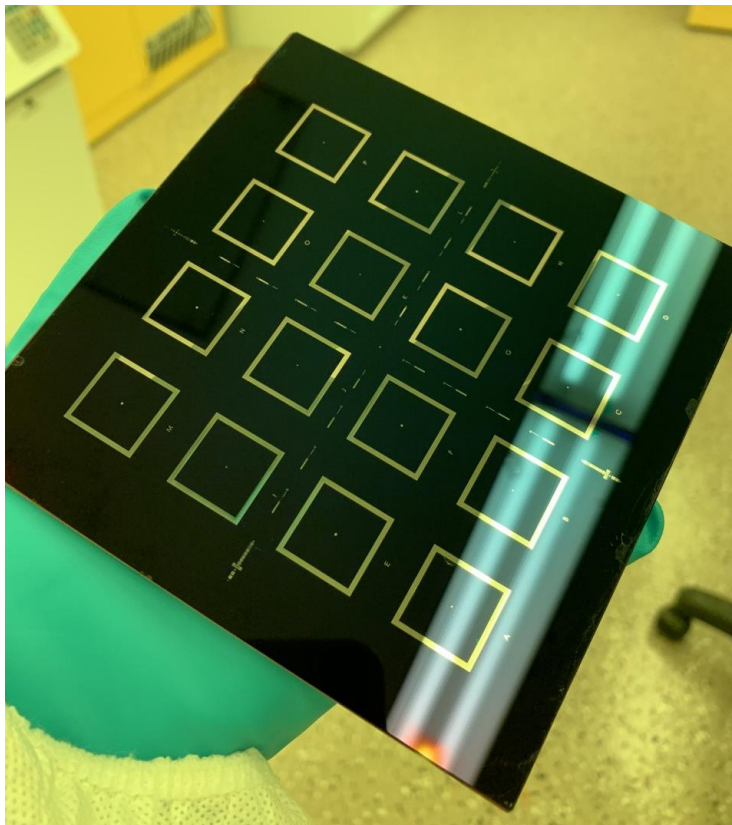


Figure 65. Actual image of full DPM on-chip substrate.

8.7.2 Defocus Test During Lithographic Exposure

One selects a lithography tool based on its ability to resolve the smallest features of a design while exposing the entire desired pattern in a timely manner. The Heidelberg

instrument is a photolithography tool known for its maskless advantage. Rather than spend additional time fabricating new and/or multiple hard masks for a substrate, one can use virtual masks created in AutoCAD for direct writing with the system. Cleanroom facilities at the University of Illinois Urbana-Champaign house two Heidelberg systems: the Heidelberg uPG 101 in the Holonyak Micro and Nanotechnology Lab (HMNTL), which has an impressive lateral resolution of 0.6 μm , and the Heidelberg MLA150 in the Materials Research Lab (MRL), which has an adequate lateral resolution of 1.0 μm .

When using the Heidelberg uPG 101, there is a trade-off between resolution and write time. The system has two write-heads of different dimensions: 2 mm and 10 mm, with the former providing higher resolution in exchange for a slower write time and smaller write area. During one trial, the author used the 2 mm write head to pattern the pinhole and aperture. The 10 mm write head was used to pattern the e-beam alignment marks discussed further in the upcoming Pinhole and Aperture Fabrication with HMNTL Lens section.

During recipe optimization, the power, filter, and defocus parameters were set based on which write head was used. For the 2 mm write head, power was set to 2 mW. The associated filter and defocus values were 80% and -9, respectively. For the 10 mm write head, 9 mW of power was used. The filter and defocus were set to 70% and -5, respectively. These values were pre-determined by research engineer Karthick Jeganathan and worked well.

The Heidelberg MLA150 required different parameters to resolve a 1 μm diameter pinhole. The author determined the optimal exposure dose and defocus parameters for this system and AZ 1518 photoresist using the built-in defocus test of the system. First, a mask pattern with features on the scale of the on-chip device was designed (see Fig. 66): The

author included pinholes of various radii ranging from 0.5 – 8 μm . Two apertures with 100 μm and 120 μm diameters were also included.

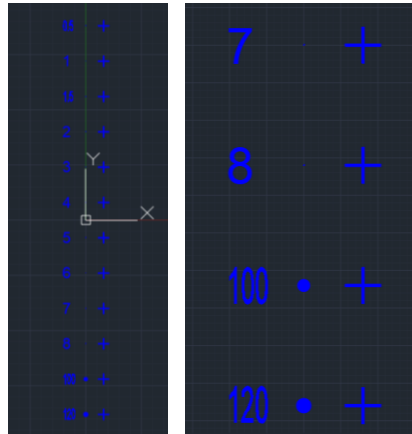


Figure 66. AutoCAD mask of Heidelberg dose test design. (a) Full design. Pinhole radii ranged from 0.5 – 8 μm . Pinhole labels were $\sim 300 \mu\text{m}$ in width. (b) Enlarged image of mask showing pinholes located in between size label and 300 μm x 300 μm crosshairs.

After importing the design into the Heidelberg and converting the file, dose and defocus ranges were chosen. Dose was varied from 60 – 150 mJ/cm^2 in increments of 10 mJ/cm^2 . Defocus values were varied from -4 to 3 in increments of one. The Heidelberg replicated the design across the substrate using a total of 80 dose and defocus combinations. Defocus values increased horizontally across the sample while dose increased in the -y direction (see Fig. 67).

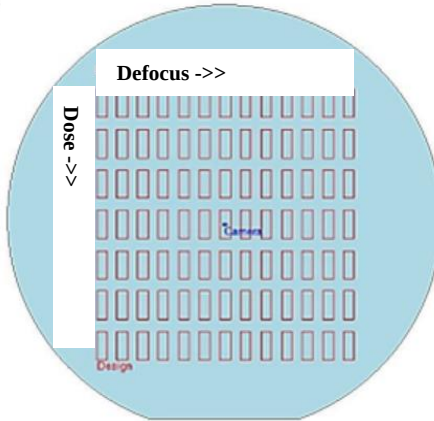


Figure 67. Dose and defocus test template in Heidelberg MLA150.

Dose and defocus can affect feature resolution. In particular, the defocus value appeared to affect the spread of the pinhole (as seen in Fig. 68). Defocus values -1, 0, and 1 produced an elliptical pinhole rather than a circular one post-development. The optimal values obtained after this test included a dose of 60 mJ/cm² and a defocus of -3. Figure 69 shows the corresponding images of two apertures created with the optimal values.

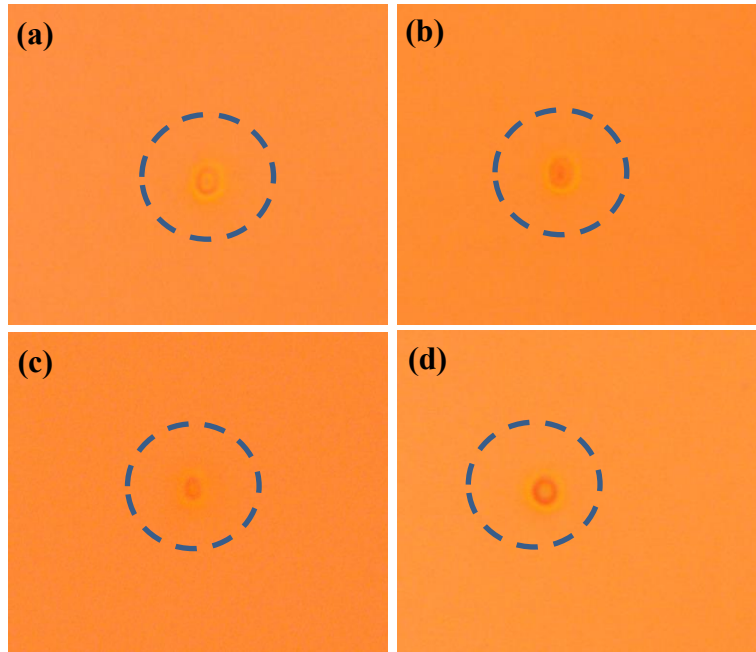


Fig. 68. Optical images of 1 μm diameter pinholes fabricated with varying defocus values. Dose was set to $60 \text{ mJ}/\text{cm}^2$. Defocus values were (a) 0, (b) -1, (c) 1, and (d) -3.



Figure 69. Two apertures fabricated with the optimal Heidelberg dose and defocus parameters for AZ 1518 photoresist.

8.7.3 Pinhole and Aperture Fabrication with HMNTL Lens

Arranging the pinhole and aperture on the same substrate as the HMNTL lens involves a more complex process. Though the same procedure was used to fabricate the pinhole and aperture for this case also, additional steps were necessary. To add a self-aligned Fresnel lens directly to the substrate, backside alignment marks are required. These marks were added using the EVG 620 Double-Sided Mask Aligner. The photolithography procedure is discussed below.

After fabricating the pinhole and aperture on the surface (i.e., side A), the opposite side was cleaned using a standard degreasing recipe. Then AZ 5214 photoresist was spun onto side A as a protection layer. The substrate was baked at 110 °C for two minutes. Next, 10 nm of chromium and 80 nm of gold were deposited onto the clean quartz surface via thermal evaporation. Note that chromium served as an adhesion layer for the gold. Hexamethyldisilazane (HMDS) was then added to prime the gold surface for photoresist adhesion. AZ 5214 was chosen based on its image reversal capability.

Because the EVG 620 requires a hardmask to pattern a substrate, the author used the Heidelberg uPG 101 to create one. The hardmask containing the e-beam alignment marks was developed and etched using the recipe discussed previously. Figure 70 shows microscope images of EVG alignment marks on a final hardmask post-etch.

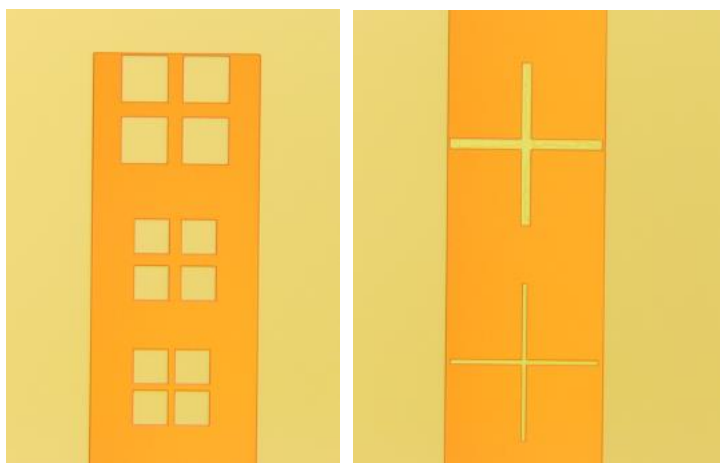


Figure 70. Alignment marks etched onto a hardmask used with the EVG 620 Double-Sided Mask Aligner. The crosshairs shown are on the scale on 290 μm in length and 10 μm in width.

The substrate was exposed to the hardmask using a dose of 15 mJ/cm^2 . Then, the sample was hardbaked for 2.5 minutes at 110 $^{\circ}\text{C}$. Additional time was needed because aluminum foil was added to the hotplate to protect it from photoresist baked onto side A. A flood exposure of 75 mJ/cm^2 was used to implement image reversal. Afterwards, the sample was developed in AZ 340 developer for 30 seconds. The sample was descummed with oxygen plasma for two minutes at 250 W. Lastly, a gold etch and a chromium etch were performed for approximately 32 seconds and 5 seconds, respectively.

The author has yet to fully integrate the HMNTL lens with the substrate described in this section, as the lens is still being characterized and tested on a separate practice substrate (i.e., a 1 mm thick glass slide). As mentioned previously, we are still attempting to determine why the grayscale e-beam lithography is not producing the correct step heights for each layer. Once the e-beam recipe is optimized, we can replicate the substrate using the optimized recipe. Figure 71 shows an e-beam alignment mark with a separate line length of 250 μm and a linewidth of 5 μm .

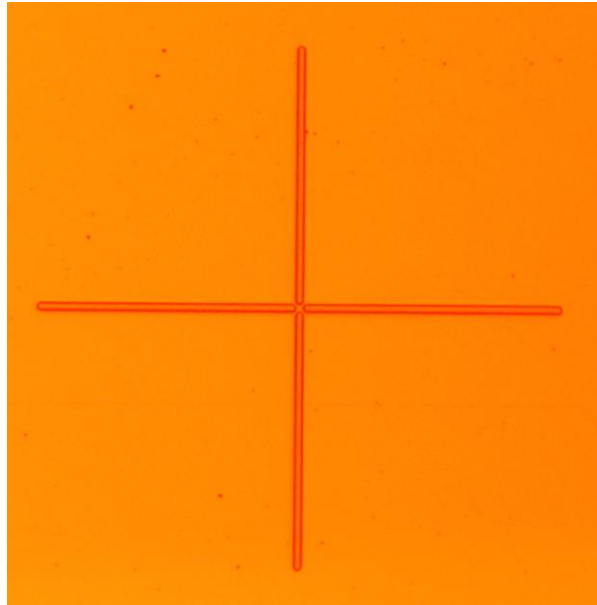


Figure 71. E-beam alignment marks developed onto a test substrate. The crosshair linewidth is 5 μm . Its separate lines are 250 μm in length.

9. On-Chip Characterization and Testing

Profilometry was used to measure the height and surface roughness of the Edmund Optics Fresnel lens without creating visible artifacts. The tool appears to output accurate height values at zone transitions due to the tiny 2 μm radius of the stylus. A camera integrated within the Dektak system was also used to characterize the profile of the Edmund Optics Fresnel lens. To view the profile of the HMNTL Fresnel lens, an atomic force microscope (AFM) was used. The AFM tool had better than one-nanometer resolution capability. Such high resolution was unnecessary for our characterization, because the smallest zone width of the ideal lens was 330 nm. A scanning electron microscope (SEM) was avoided due to lens height being significantly less than the lateral dimension and because the electrons from the SEM might deform the shape of the resist.

9.1 Fresnel Lens Testing

The standard convention for testing a Fresnel lens is to use it as intended. Because the light for DPM on-chip focuses so closely to the substrate (i.e., within the pinhole and aperture), the lenses were challenging to test. The author initially tested the focusing capability of the purchased lenses by imagining a small ruler. A cellphone camera and ambient lighting facilitated the process. During testing, the author confirmed that the orientation of the Fresnel lens was important. Figure 72 showcases what occurred when the Fresnel lens was oriented in two different directions.

First, the lens was placed over the camera detector, which had auto-focusing capability. Next, the ruler was placed a focal length away from the lens. Note that Fresnel lenses are

rarely used in imaging applications because of reduced image quality compared to that of conventional aspherical lenses; nonetheless, one can clearly see the focused centimeter markings on the ruler in Fig. 72 when the grooves faced toward the light source. There was a notable difference in the field of view when switching orientations. A larger region was in focus when the lens was oriented correctly.



Figure 72. Imaging a Fresnel lens using different orientations. A lens with a 5 mm focal length was used to image centimeter markings on a ruler. The correct orientation produces the image on the left. The image on the right is caused by improper lens orientation.

After characterizing the commercial Fresnel lenses, the author discovered that these lenses are normally fabricated using micro-milling techniques during mass production rather than more precise lithographic techniques [32]. Defects were evident on the sample. As a result, we realized the need to account for tolerance in the focal length. Note that when ideal zone profiles are not achieved, there is also a direct effect on diffraction efficiency. The author redesigned the device (i.e., developed Design #3) to counter unintended focal length variation. For this design, the pinhole/aperture substrate was separated from Lens 2. Next, the focal length of Lens 2 was increased to offset the separation distance. Spacers

were added to ensure that the grating and the Fourier filter were positioned the correct distance from each Fresnel lens. Figure 73 shows a schematic of Design #3.

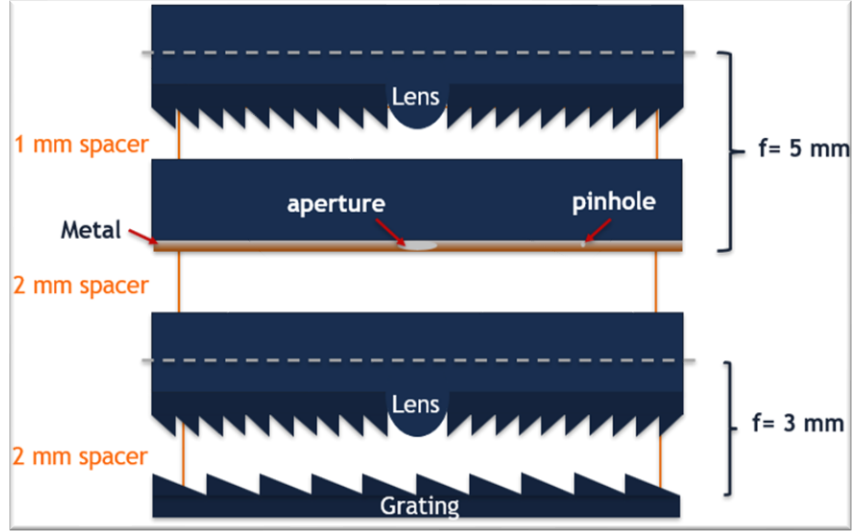


Figure 73. Schematic of DPM On-Chip Design #3. The design was adjusted to enable flexibility in pinhole position during alignment.

The optical adhesive NOA 85 was initially used to adhere metal spacers to the glass optics; however, full curing never occurred. This is likely because the various light sources used during the process, did not output the correct wavelength and wattage required for complete curing. As a result, the author used DAP RapidFuse for subsequent bonding, being careful to avoid all areas where light would traverse.

9.2 DPM On-Chip Module Testing

The chip-scale DPM system was separated into two modules for Design #3: one containing the grating and Lens 1 and the other containing the Fourier filter and Lens 2. These two modules replaced their macro-DPM counterparts during final testing. Two metal housings were connected to a Thorlabs PT3 1" translation stage with ZST225B actuators

to enable submicron-precision alignment of the modules. The first module was examined with an Amscope camera to determine whether sample features would resolve. Unfortunately, results demonstrated that Fresnel lenses are impractical for a chip-scale DPM system. Results are discussed in detail below.

Figure 74 showcases the resulting image produced by the first module of Design #3. A second lens with $f = 25$ mm was used to focus the conjugate sample plane onto a recessed camera detector. Although the zones of the Fresnel lens were visible regardless of whether the camera was placed a correct distance from the second lens, sample features remained indistinguishable. Next, the author attempted to see whether a single Fresnel lens could image the sample without the grating. The sample was translated laterally to compare the resulting image associated with a flat region to that of a region containing structures. Though a change in the image did occur after stage translation, the resulting image did not correspond to any known features of the sample. Figure 75 shows the result of imaging a flat region with the Fresnel lens. Figure 76 shows indistinguishable sample features that appear after stage translation in addition to the concentric rings of the lens.

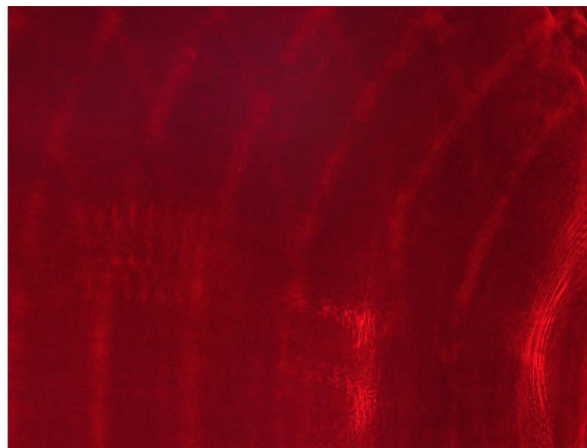


Figure 74. Image of DPM on-chip module. The concentric rings of the Fresnel lens were the only objects imaged clearly.

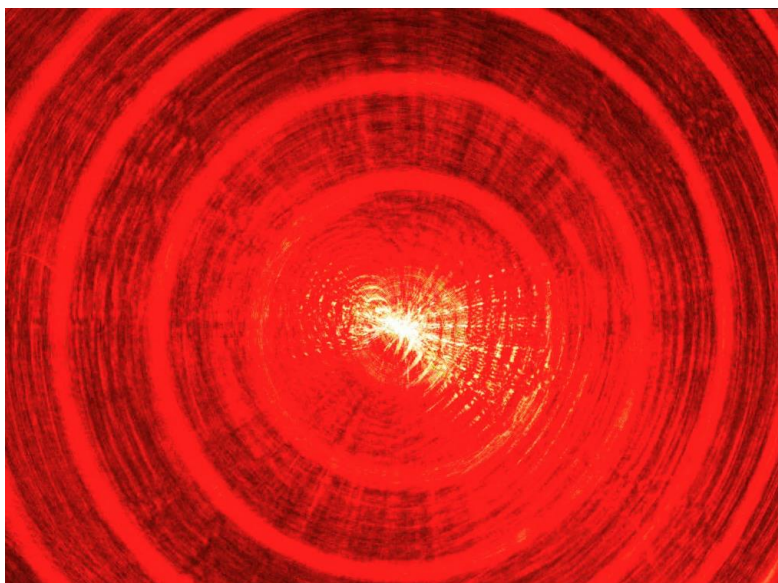


Figure 75. Sample image taken after removing the diffraction grating. When flat regions of the sample were imaged, only concentric rings of the Fresnel lens could be seen.

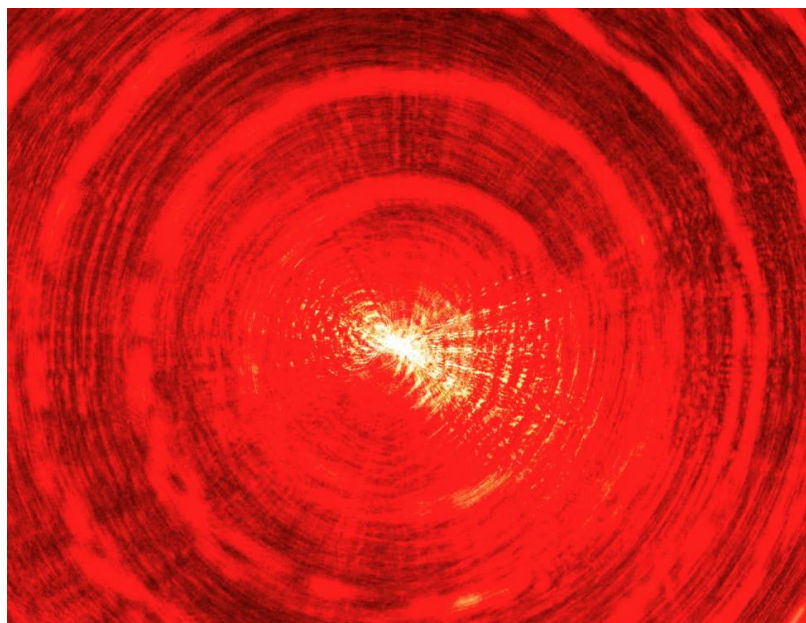


Figure 76. Sample image taken after stage translation. When regions containing raised features were imaged, numerous ripples appeared in the captured image.

After conducting a second search of the literature, it appears that the resulting images are likely attributed to three causes: the discontinuous edges of the Fresnel lens, insufficient accuracy in placing optical elements, and the use of coherent light with these specialized lenses.

The discontinuous edges contribute to increased scattering within the Fresnel lens. In general, Fresnel lenses are not as good as bulk spherical or aspheric lenses in high performance imaging applications because of this scattering, which manifests itself as concentric rings of saturated intensity, even at low power (i.e., less than 1 mW) [33]. Exacerbating this issue, the Edmund Optics Fresnel lens had a lower groove density and thus larger step discontinuities than the planned high groove density HMNTL Fresnel lens. The larger discontinuities will result in more scattering and poorer image quality [34].

On the small scale associated with micro-DPM, inaccurate spacing of optical elements, translational misalignment, and angular misalignment are each detrimental to image quality. Given the short 3 mm and 5 mm focal lengths, the necessary accuracy for positioning optical elements is sub-millimeter in all 3 dimensions. Additionally, when features were present in the sample, the sloped profile of each zone caused the light to bend into “slightly non-focusing angles” that resulted in ripples [35].

Initially, the author did not consider the effect of imaging with a coherent source versus an incoherent source because DPM can be used with either provided that the source has adequate spatial coherence; however, it appears that light source matters for imaging with a Fresnel lens. Many applications demonstrate the use of Fresnel lenses as solar concentrators. The author also demonstrated that ambient lighting could be used with a Fresnel lens to image a ruler before integration into the micro-DPM system. Generally,

incoherent imaging techniques are well-known for their improved resolution compared to that of coherent imaging systems [36]; however, because the macro-DPM system worked well with a coherent source, the author did not realize that the outcome would vary significantly after Fresnel lens integration. There seems to be one instance in which coherent light would prove to be the better option [37]. S. Van Aert et al. determined that the phase distribution of a sample has an important effect on whether an incoherent light source is superior. They argued that if neighboring points on a sample have a π phase difference, then a coherent imaging system is preferred. For the 633 nm light used in Design #3, a π phase difference would equal 317 nm. Our actual sample structures had a height difference of 160 nm. Therefore, a coherent light source would not be optimal for this case. Additionally, many samples that could be used with a functioning micro-DPM system would likely have varying heights, so a coherent light source with a Fresnel lens might prove limiting. Replacing the laser with an incoherent source for future work might improve micro-DPM; however, the author believes that the best course of action is to replace the Fresnel lenses with conventional micro-lenses or aspheric lenses with short focal lengths. A fourth design will be discussed in the Future Work section.

10. Application

Design #3 for DPM on-chip has a 41- μm field-of-view. As a result, using the system to examine the morphology of bacteria, viruses, and certain animal cells would be feasible. Because Design #3 no longer utilizes UVA radiation, examination of such samples is now possible without damaging the living cells. Additionally, the author proposes utilizing a functional DPM on-chip device for industrial applications, such as microlens characterization. Microlens arrays are used to concentrate light onto photodiodes in cameras. Their size can range from tens of microns to millimeters. DPM on-chip can be used to quickly and non-invasively image these phase objects. It can provide insight into lens height and topography (i.e., defects, curvature, etc.). If desired, one can expand the number of DPM on-chip applications by adjusting parameters such as pixel width and 4f magnification appropriately.

DPM on-chip also has the potential to be used in a new application: portable microscopy. If DPM on-chip is integrated as an add-on module to a cellphone camera, the image processing could be executed within a cellphone application. Such a system might prove useful in biological labs with limited space for testing instruments. It might also be beneficial in biology classrooms that attempt to spark curiosity within younger citizen scientists.

10.1 Macro-DPM vs. Micro-DPM Trade-off

If both DPM systems functioned optimally, there would ultimately be a compromise in FOV when switching from macro- to micro-DPM. At one point during testing, we reduced

NA_{obj} and M_{obj} for the micro-system in order to expand the FOV, but this decreased the resolution of our system. Nonetheless, let us consider cases when these values are held at 0.8 and 20, respectively, for both systems. Table 10 shows the resulting diagonal FOV when switching between macro- and micro-DPM. Both the 4f magnification of the lenses and the camera pixel width contribute to significant changes in the FOV. For example, if one were to reduce the magnification of the macro-system from its standard value of five for macro-DPM to one for micro-DPM, a FOV on the scale of 1 mm could be achieved. Note that micro-DPM maintains a smaller FOV due to the limiting pinhole size of 1 μm . The FOV for micro-DPM must be manually cropped during image processing to ensure the intensity and phase profile of the illumination exiting the pinhole is roughly constant across the FOV.

Table 10. The effect of parameter variation on FOV.

<u>System</u>	<u>Camera</u>	<u>4f Magnification</u>	<u>Diagonal FOV</u>
Macro-DPM	Hamamatsu	5	109 μm
Macro-DPM	Amscope	5	77 μm
Macro-DPM	Amscope	1	1020 μm
Micro-DPM	Amscope	1	41 μm

11. Future Work

As previously mentioned, future work will entail improving the HMNTL Fresnel lens. More characterization must occur so that desired step heights are obtained. Additionally, the author suggests fabricating a scaled down system using conventional lenses that have small focal lengths (i.e., Design #4) because Fresnel lenses may be impractical with the DPM setup. Although the results will not be discussed in this thesis, we are currently working to replace Lens 1 and Lens 2 with aspherical micro-lenses that have an 8 mm and a 25 mm focal length, respectively. The camera sensor is recessed inside its housing by about 20 mm. Thus, 25 mm was chosen for the focal length of lens 2 to minimize the overall system size (66 mm total length) while still enabling lens 2 to directly mount to the front of the threaded camera housing. So far, successful images have been obtained without integrating a Fourier filter or grating. The author will integrate these components next to determine whether micro-DPM is possible when used with conventional lenses.

Because we have not completely ruled out the use of Fresnel lenses with micro-DPM, one might attempt to replace the laser with a broadband source to address source coherence, to use a higher groove density Fresnel lens to minimize scattering, and to use longer focal length Fresnel lenses to alleviate the tight alignment tolerances. After examining the images obtained in this scenario, it will be possible to determine whether Fresnel lenses should completely be removed from micro-DPM consideration.

11. 1 Fabrication with Conventional Micro-Lenses

After determining whether conventional micro-lenses will work in a scaled-down system, one might consider fabricating the lenses on a quartz substrate in this case also. Lens 1 would mount to the grating directly with an air spacer in between as discussed in previous designs. Metal spacers could still be used in this scenario. The advantage of using conventional lenses includes not having to account for an additional shift in the pinhole and aperture spacing that occurs with a Fresnel lens. Because diffractive elements would no longer be used, the separation distance constraint should follow the original equation.

11.2 Anti-Reflective Coating for Fourier Filter

To improve the overall micro-DPM system, one might also utilize an anti-reflective coating on the pinhole/aperture substrate so that back reflections in the system are reduced. Because chromium was chosen as the optimal substrate metal in this case, one could introduce a buffer layer, or anti-reflective coating, with refractive index $n_{buffer} = \sqrt{n_{chromium}n_{quartz}}$ and thickness $t = \frac{\lambda}{n_{buffer}}$ that would result in incident and reflected rays canceling from destructive interference [38]. For DPM on-chip involving a broadband source, one could use multiple layers for anti-reflection (see Fig. 77) [30]. Although this anti-reflective coating is sensitive to buffer thickness and incident angle, it is cost-effective.

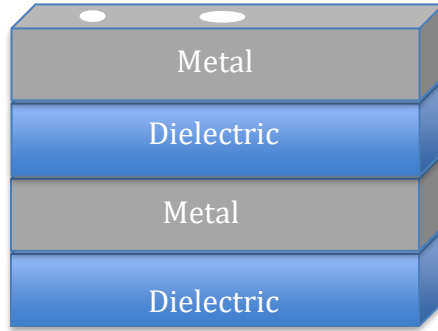


Figure 77. Antireflective coating. Using a multilayer stack of metal and dielectric layers is a proven technique to reduce reflections at an interface. For a broad spectrum, numerous layers are required.

An alternative to the multi-layer stack would be a rough surface with cone-shaped anti-reflective elements having height equal to a half-wavelength (see Fig. 78) [38]. This technique has been used for light trapping in solar technology. The addition of a rough surface emulates an antireflective coating with a varying refractive index. This implies that a rough surface will operate under a range of wavelengths. Feature sizes (i.e., the grating period) should be smaller than the wavelength. If the grating is not sub-wavelength, multiple reflections will occur, and light will likely enter the material.

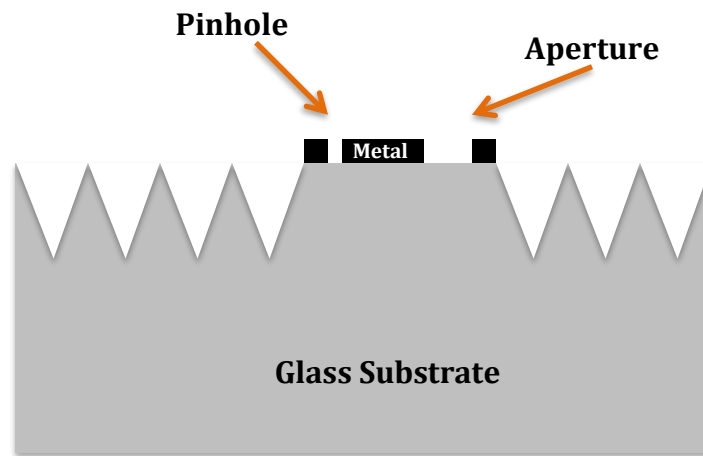


Figure 78. Texturized surface to block reflection. A moth's eye structure is used in solar cell technology to trap light (i.e., prevent reflections at an interface). It can be used in the prototype shown in the figure to prevent light traveling from the Fresnel lens from reflecting in the substrate. Cone height equals $\lambda/(n-1)$.

12. References

- [1] "History of the cell: discovering the cell," *National Geographic* (2019). [Online.] Available: <https://www.nationalgeographic.org/article/history-cell-discovering-cell/>. Accessed 1 Aug. 2020.
- [2] W. Xu, Y. Zhang, and T. Chen, "X-ray-based microscopy of single-particle nanocatalysis," *Single Particle Nanocatalysis: Fundamentals and Applications*, Wiley, 2019.
- [3] F. Zernike, "Phase contrast, a new method for the microscopic observation of transparent objects, Part 1," *Physica*, Vol. 9, pp. 686-698, 1942.
- [4] "Phase contrast microscopy," *Nature* (2020). [Online.] Available: <https://www.nature.com/milestones/milelight/full/milelight05.html>. Accessed 1 Aug. 2020.
- [5] D. B. Murphy et al., "Introduction to phase contrast microscopy," *Microscopy U*. [Online.] Available: <https://www.microscopyu.com/techniques/phase-contrast/introduction-to-phase-contrast-microscopy>. Accessed 1 Aug. 2020.
- [6] L.C. Martin, "Phase-contrast methods in microscopy," *Nature*, Vol. 159, No. 405, pp. 827-830, 1947.
- [7] F. Zernike, "Phase contrast, a new method for the microscopic observation of transparent objects, Part 2," *Physica*, Vol. 9, pp. 974-986, 1942.
- [8] B.E.A. Saleh and M.C. Teich, "Wave optics," *Fundamentals of Photonics*, 2nd ed., Wiley & Sons, 2007.
- [9] B. Bhaduri, et al., "Diffraction phase microscopy: principles and applications in materials and life sciences," *Adv. Opt. Photon.*, Vol. 6, pp. 57-119, 2015.
- [10] S. Ajithaprasad, J. Ramaiah and R. Gannavarpu, "Dynamic deformation analysis using diffraction phase microscopy and space-frequency analysis," *2019 Workshop on Recent Advances in Photonics (WRAP)*, pp. 1-3, 2019.
- [11] O. Kocahan, et al., "Quantitative phase imaging of red blood cell by diffraction phase microscopy," *2017 Computing and Electromagnetics International Workshop (CEM)*, pp. 21-22, 2017.
- [12] G. Popescu, *Quantitative Phase Imaging of Cells and Tissues*, McGraw-Hill, 2011.

- [13] V. Bansode and R. John, "Characterization of microstructures using white light diffraction phase microscopy," *2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI)*, pp. 2394-2398, 2017.
- [14] D. C. O'Shea, et. al., *Diffraction Optics: Design, Fabrication, and Test*, SPIE, 2003.
- [15] "Visible Transmission Gratings," *Thorlabs*, 1999. [Online]. Available: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=1123. Accessed 1 Aug. 2020.
- [16] J. R. Egger, "Use of Fresnel lenses in optical systems: some advantages and limitations," *Proc. SPIE 0193, Optical Systems in Engineering I*, 1979.
- [17] A. Stein et al.; "Fabrication of silicon kinoform lenses for hard x-ray focusing by electron beam lithography and deep reactive ion etching;" *Journal of Vacuum Science and Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*; Issue 1, 2008.
- [18] A. Siudzińska, A. Miszczuk, J. Marczak, and K. Komorowska, "Fluorescent sensing with Fresnel microlenses for optofluidic systems," *Opt. Eng.* Vol. 56, No. 5, 2017.
- [19] "Sag calculator," *Edmund Optics*. [Online.] Available: <https://www.edmundoptics.com/knowledge-center/tech-tools/sag/>. Accessed 1 Aug. 2020.
- [20] C. P. Chen, et al., "Silicon Fresnel lens fabricated using greyscale lithography," *Proc. SPIE 11104, Current Developments in Lens Design and Optical Engineering XX*, 2019.
- [21] T. Fujita, H. Nishihara, and J. Koyama, "Fabrication of micro lenses using electron-beam lithography," *Opt. Lett.*, Vol. 6, pp. 613-615, 1981.
- [22] T. Fujita, H. Nishihara, and J. Koyama, "Blazed gratings and Fresnel lenses fabricated by electron-beam lithography," *Opt. Lett.*, Vol. 7, pp. 578-580, 1982.
- [23] J. E. Hergert, et al., "High-efficiency Fresnel lens design and fabrication in a two-stage photopolymer," *Proc. SPIE 11030, Holography: Advances and Modern Trends VI*, 2019.
- [24] R. Murali, "Metrology for grayscale lithography," *AIP Conference Proceedings*, Volume 931, pp. 419-422, 2007.

- [25] H. Yin, J. Hu, and C.S. Yu, "The study on 3D electron beam lithography for sub-micrometer diffractive optics," *2007 IEEE/LEOS International Conference on Optical MEMS and Nanophotonics*, Hualien, pp. 149-150, 2007.
- [26] J.D. Rogers, et al., "Realization of refractive microoptics through grayscale lithographic patterning of photosensitive hybrid glass," *Opt. Express*, Vol. 12, pp. 1294-1303, 2004.
- [27] T. Nachmias, et al., "Shallow Fresnel lens fabrication using grayscale lithography made by high energy beam sensitive mask (HEBS) technology and reactive ion etching," *Proc. SPIE 7205, Advanced Fabrication Technologies for Micro/Nano Optics and Photonics II*, 2009.
- [28] C. Michel, J. Loicq, T. Thibert, and S. Habraken, "Optical study of diffraction grating/Fresnel lens combinations applied to a spectral-splitting solar concentrator for space applications," *Appl. Opt.*, Vol. 54, pp. 6666-6673, 2015.
- [29] N. Ahmad, et al., "Ultra-thin metal films for enhanced solar absorption," *Nano Energy*, Vol. 1, No. 6, pp. 777 – 782, 2012.
- [30] M. Susa, R. K. Endo, "Emissivities of High Temperature Metallic Melts," in *High-Temperature Measurements of Materials. Advances in Materials Research*, Vol 11, Springer, pp. 111 – 129, 2009.
- [31] P. Malinský, et al., "Early stages of growth of gold layers sputter deposited on glass and silicon substrates," *Nanoscale research letters*, Vol. 7, No. 241, 2012.
- [32] R. M. Vázquez, et al., "Fabrication of binary Fresnel lenses in PMMA by femtosecond laser surface ablation," *Opt. Express* 19, pp. 11597-11604, 2011.
- [33] C. R. Nave, "Fresnel Lens," *Hyperphysics* (2001). [Online]. Available: <http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/fresnellens.html>. Accessed 18 Apr. 2022.
- [34] "Advantages of Fresnel Lenses," *Edmund Optics* (2022). [Online.] Available: <https://www.edmundoptics.com/knowledge-center/application-notes/optics/advantages-of-fresnel-lenses/>. Accessed 18 Apr. 2022.
- [35] M. Zhong and H. Gross, "Phase space of partially coherent light with discontinuous surfaces," *Journal of the European Optical Society-Rapid Publications*, Vol. 12, No. 3, 2016.
- [36] G. Zheng, "Basic concepts in Fourier optics," *Fourier Ptychographic Imaging*, Morgan & Claypool Publishers, 2016.

- [37] S. V. Aert, D. V. Dyck, and A. J. den Dekker, "Resolution of coherent and incoherent imaging systems reconsidered - Classical criteria and a statistical alternative," *Opt. Express* 14, pp. 3830-3839, 2006.
- [38] C.S. Schuster, "Diffractive optics for thin-film silicon solar cells," *Springer International Publishing*, 2017.

13. Scripts for Image Processing and Fresnel Lens Fabrication

13.1 Phase Retrieval for DPM System

The code for phase retrieval is shown below. The original code was written by Dr. Lynford Goddard and was modified by Dr. Goddard and Lonna Edwards for this application.

```
%% DPM Phase Retrieval for Amscope MU1803. Original code by Lynford ____
% Goddard and modified by Lynford Goddard and Lonna Edwards
% N represents pixels in x, M represents pixels in y
%
% (v0,u0) is +1 order pixel position relative to center pixel with +1
% along x direction
% D is +1 order radius in pixels. Approx. |v0/3|

N = 4912;
M = 3684;
u0 = 5;
v0 = 318;
D1 = 106;

image =
imread('C:\Users\ldedwar2\Desktop\3_02_22\70mA_8p1_23p9_8p75.png');
calib_image =
imread('C:\Users\ldedwar2\Desktop\3_02_22\70mA_8p2_24p2_8p75.png');

image = rgb2gray(image);
calib_image = rgb2gray(calib_image);

%% Create a mask
[X,Y] = meshgrid(1:N,1:M); % 2D spatial coordinates [pixels]
mask = zeros(M,N);
r = zeros(M,N);
r = sqrt((Y-M/2-u0).^2 + (X-N/2-v0).^2); % 2D radius [pixels]
mask(r<=D1) = 1.0;

%% Implement the DPM Interference to Complex conversion on measured and
calibration images
% Output is z = Amplitude(x,y) * exp(j beta x + phi(x,y));

z = ifft2(fftshift(fft2(image)).* mask);
z_calib = ifft2(fftshift(fft2(calib_image)).* mask);

%% Implement the Complex to log10(Amplitude) and Phase conversion
% Output is the amplitude and wrapped phase

temp = z./ z_calib;
amplitude = 10*log10(abs(temp));
phase = atan2(imag(temp),real(temp));

%% Implement Phase Unwrapping
unwrapped = unwrap2(phase);
```

```

%% Compute Height
lambda = 642;
height = phase*lambda/(4*pi);
height_unwrapped = unwrapped*lambda/(4*pi);

%% Average a specific region (edits by LG 4/11/22)
height_unwrapped2 = height_unwrapped;
avg1 = mean2(height_unwrapped2(500:1500,100:1000));
avg2 = mean2(height_unwrapped2(2500:3500,2000:3000));
avgheighttitle = sprintf('Net avg height of boxes %g or %g (nm)', avg1-
avg2, avg1-avg2+lambda/2);
height_unwrapped2(500:1500,100:1000) = NaN;
height_unwrapped2(2500:3500,2000:3000) = NaN;

%% Plot Results (edits by Lonna & LG)
figure(1)
subplot(2,4,1); imagesc(height); title('Height (nm)'); colorbar;
subplot(2,4,2); imagesc(height_unwrapped); title('Unwrapped Height
(nm)'); colorbar;
subplot(2,4,3); imagesc(height_unwrapped2); title(avgheighttitle);
colorbar;
subplot(2,4,4); imagesc(amplitude); title('Amplitude (dB)'); colorbar;
subplot(2,4,5); imagesc(phase); title('Phase (rad)'); colorbar;
subplot(2,4,6); imagesc(unwrapped); title('Unwrapped (rad)'); colorbar;
subplot(2,4,7); imagesc(10*log10(abs(fft2(image).* mask)));
title('Image FFT amplitude with mask (dB)'); colorbar;

```

13.2 Radii of Fresnel Zones

The code below outputs the outer radii of each Fresnel zone associated with the HMNTL lens. It was written by Lonna Edwards.

```
% DPM Fresnel lens code written by Lonna Edwards
%DPM fresnel lens with N subdivisions, no plot
clear all;
format bank;

D = 1.44*10^-3; %lens diameter
N = 8; %number of subdivisions per 2pi zone
f = 3.0*10^-3; %focal length
lambda = 633*10^-9;
MaxRadii = 100000;

tic
m = 1:MaxRadii;
r_out = sqrt(2*m*f*lambda/N); %1-D matrix in y with r_out values
r_out_filtered = r_out(r_out<=D/2); %outer radii less than lens radius
note LE
d_out_filtered_microns= 2.*r_out_filtered*10^6

num_radii = length(r_out_filtered);
r_in_filtered = [0 r_out_filtered(1:num_radii-1)]; %inner radii note LE
d_in_filtered_microns= 2.*r_in_filtered*10^6 %input for CAD as diameter
not radius

for h = 1:N
    s = sprintf('Layer%d.txt',h);
    fid = fopen(s,'w');
    for j=h:N:num_radii
        fprintf(fid,'%16f %16f 0,0\r \r', d_in_filtered_microns(j),
d_out_filtered_microns(j)); %remove exponent and add center point
    end
    fclose(fid);
end

toc
```